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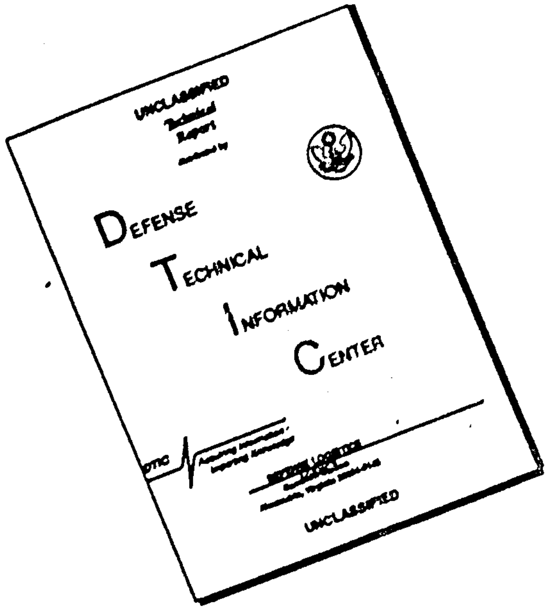

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SELF-CONSISTENT BLAST WAVE PARAMETERS

Prepared for: DEFENSE ATOMIC SUPPORT AGENCY
Under DASA Contract No. DA-49-146-XZ-293

Written by: R. R. Mills, Jr., F. J. Fisch, B. W. Jezek, W. E. Baker
as an AAI Engineering Report ER-3589

OCTOBER 1964

AIRCRAFT ARMAMENTS, Inc.
COCKEYSVILLE MARYLAND 21030

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TABLE OF CONTENTS

		Page No.
I.	INTRODUCTION	1
II.	AIR BLAST DATA SOURCES	3
	A. Data Source Discussion	4
	B. Evaluation of Available Information	18
III.	AIR BLAST PROPERTIES INFERRED FROM THEORY	23
	A. Theory Prior to 1947	23
	B. Recent Computations	25
IV.	COMPARISONS OF EXPERIMENT AND THEORY	31
	A. Shock-Front Parameters	31
	B. Time Histories of Blast Parameters	35
	C. Ground Reflection Factors	36
	D. TNT-Pentolite Conversion Factors	37
V.	PRESENTATION OF SELF-CONSISTENT DATA	39
VI.	DISCUSSION	41
VII.	REFERENCES	44
	Appendix	50
	A. Blast Parameters Based on Sachs' Scaling Laws	50
	B. Rankine - Hugoniot Relationships	52

I. INTRODUCTION

In this study, we are concerned with the determination and graphical presentation of a self-consistent set of blast wave properties for a TNT explosive. These data can then be utilized to predict the characteristics of the resulting blast field environment. It is to be noted that a similar study by Baker and Schuman[1*] can be used to predict the blast environment generated by a Pentolite explosive source.

The following sections of this report will review the available sources of experimental data on blasts from both TNT and Pentolite in order to provide the reader with a comprehensive listing of such sources of data. The TNT data from a selected number of these references will be compared to the various theoretical prediction techniques that are available, in order to define the factor(s) necessary to effect agreement between the experimental data and the theoretically predicted magnitudes of these data. Finally, a series of graphs will be presented that will provide a self-consistent set of air blast parameters for explosive detonations of TNT in air. Where appropriate, methods of accounting for ground reflection effects and conversion from TNT to Pentolite explosive will be discussed.

The previous study conducted by Baker and Schuman[1] resulted in a similar set of air blast parameters for Pentolite detonations. However, this study was based on correlating the shock-front parameters, as compiled by Goodman[2] from experimental data obtained from Pentolite detonations, with plots of data behind the shock front obtained from the theoretical predictions of Brode[3] for TNT

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* Superscript numbers denote references in Section VII.

detonations. Adjustments were made by the authors of reference 1 to account for the difference in type of explosives, and to match the theoretical analyses with the experimental data along the shock front. However, the theoretical TNT analyses could not be adjusted to exact coincidence with the Pentolite experimental results; furthermore, the analyses of Brode[3] exhibited internal inconsistencies that could not be overcome.

In this study, we will attempt to eliminate some of the inconsistencies of reference 1 by comparing TNT experimental data with a theoretical prediction technique based on a TNT detonation. It is to be noted that the theoretical analysis selected in this study does not suffer from internal inconsistencies as does the data predicted by Brode[3]. Moreover, this theoretical approach appears to be the best available at the present time in that it provides better agreement with actual experimental data than does the theory advanced by Brode.

The self-consistent set of blast parameters presented in this report have been generated for DASA under DASA Contract No. DA-49-146-VXZ-293. In addition, the theoretical computations were performed by NOL using their "Wundy 75" Code. AAI wishes to acknowledge the kind cooperation of personnel of both of these agencies during preparation of this report.

II. AIR BLAST DATA SOURCES

In Part A of this section we will summarize the contents of various references that provide experimental data defining the blast wave characteristics that result from detonations of both Pentolite and TNT explosives. The data obtained from a selected number of the TNT references will be used in latter sections of this report to graphically formulate the self-consistent set of blast wave properties for this explosive.

It is to be noted that the data sources discussed in this section do not represent an exhaustive listing of all available references; however, these sources have been judiciously chosen to provide a representative cross-section of the presently available, experimentally derived, information. These data sources are referenced in Section VII of this report.

Following the discussions of these data references, a comprehensive chart that defines the type of explosive, ambient conditions, the scaled distance range covered by the collected data, and the type of blast wave properties measured in each reference discussed in this section, is presented.

In Part B of this section, an evaluation of these data source references is given in terms of the applicability of the information contained in these references to the formulation of a self-consistent set of blast wave properties. The conclusions drawn in this discussion will dictate the selection of data to be used in the latter sections of this report.

A. Data Source Discussion

The graphical airblast data presented by Baker and Schuman[1] was developed primarily for use in predicting free flow blast conditions on moving airfoils. The shock front parameters presented in reference 1 have been extracted from the compiled experimental Pentolite data given by Goodman[2], whereas the data for parameters behind the shock front were obtained from the theoretical predictions of Brode[3]. Unfortunately, Brode's data could not be adjusted to provide exact agreement with the experimental data. Reference 1 recommends the following simple conversion factors to account for variation in type of explosive and for effect of ground reflection:

$$1.1 \text{ lb TNT} \approx 1 \text{ lb } 50/50 \text{ Pentolite}^*$$

and

$$\text{Free Air Weight of Pentolite} \approx 1.8 \text{ Pentolite weight on the ground}$$

The compiled experimental data reported by Goodman is based on the available air shock data for the 1945-1960 period. As noted in Table I, these data cover a range of scaled distances from 0.1373 (the charge surface) to 66 $ft/lb^{1/3}$. (The range of blast parameters presented by Baker[1] covers a scaled distance range from 3 to 60 $ft/lb^{1/3}$, since this was felt to be adequate for the airfoil vulnerability problem of primary interest in this reference). The Pentolite explosive density used by Goodman was

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* 50/50 Pentolite = 50% TNT and 50% PETN by weight

1.65 gm/cc. The side-on impulse and duration measurements are less satisfactory than the peak pressure and reflected impulse measurements. Goodman also develops analytic expressions for the side-on and reflected pressure, and the side-on and reflected impulse variations as functions of the scaled distance by a least squares polynominal fit to the compiled data.

The data reported by Weibull[4] are primarily measurements of the arrival times, shock front velocities, and positive pressure phase duration times obtained from TNT explosions, over a range of ambient pressures from approximately 4 atm to a vacuum of a few mm Hg. Included in this reference is a comparison of the shock arrival times obtained from different mixtures of TNT and Al (10%, 20%, and 30% Al), 100% TNT, and PETN explosives. Weibull also provides a set of formulae that may be used to reproduce the observed arrival and duration times with great precision. A comparison of the TNT arrival time data observed by Weibull with data compiled at Aberdeen Proving Grounds, Ballistic Research Laboratories for Pentolite explosive is given in the Appendices of this report.

Doll and Salmon[5] present data obtained from a carefully planned series of tests using 2500 lb of TNT as the explosive source. Unfortuanrely, the response time (315 cps) of the recording galvanometers appears to seriously limit the usefulness (and correctness) of these data. When plotted on an overpressure-scaled distance diagram .. data of Doll and Salmon are in disagreement with similar data from other sources; the peak pressures are too low, indicating that the recording system missed the true peak because of an excessively long response time characteristic.

As noted in the introductory paragraphs of the report by Fisher and Pittman[6], the primary intent of this work was to demonstrate the difficulty of detonating small charges of TNT and to describe a number of ways of recognizing poor TNT detonation processes. In addition, this report indicates that placing the booster half in and half out of the surface of a one-pound cast TNT charge, in contrast to central initiation, results in a detonation that produces the accepted peak air blast pressure and impulse magnitudes.

Although the major emphasis of the data reported by Baker et al[7] was to demonstrate the effect of fog and rain on the air blast characteristics from 1000 lb Pentolite charges, there were several recorded test events accomplished during clear weather. The reproducibility of these data is quite good; from a series of eight tests, with three gages at each radial location, the standard deviations of the peak overpressures vary from 0.08 to 0.55 psi, for a range of overpressure of 1.22 to 11.03 psi. A significant result of this test series is that the ground reflection factors computed from a comparison of these data with the free air data of Goodman[2] cover a range of 1.88 to 2.34 for increasing scaled distance. Ovbiously, for a detonation very close to the ground, a reflection factor greater than 2.0 is impossible, since values equal to 2.0 imply perfect reflection.* These results indicate that Goodman's[2] data is probably in error for the larger scaled distance ranges, since the data collected by Baker in this report is, as noted above, almost free from experimental inaccuracies.

* For detonations above the ground where the scaled height is an appreciable fraction of the scaled distance, reflection coefficients greater than 2.0 can be realized.

Reference 8 contains charts and graphs showing the effects of explosions as functions of such variables as charge weight and composition, type of weapon, distance from detonation, etc. The data sheets contained in this report are designed for use in prediction of the various characteristics associated with detonation of explosive charges. As such, this report is not a data reference report, but has been included in this discussion because of the unique manner in which the prediction charts are designed.

The data of Hoffman and Mills[9] presents measurements taken from detonation of 50/50 Pentolite spheres of 1/2 - 6 lb in weight. The side-on and reflected overpressure data and impulse and duration time measurements given in this report have been incorporated in the compiled data report by Goodman[2].

The reflected impulse measurements reported by Olson[10] were generated from detonation of 1 lb Pentolite spheres under reduced ambient pressures simulating altitudes up to 100,000 feet. Analysis of these data indicates that the impulse magnitudes scale according to Sachs' Laws, as discussed by Sachs[11] and Dewey and Sperrazza[12], although this is to be viewed with caution, as noted by Olson. This is primarily due to the fact that one of the impulse measurements, when scaled according to Sachs' Law falls inside the charge surface ($Z = .1323\ ft/lb^{1/3}$). The measurements taken by Dewey and Sperrazza[12], and subsequent discussion of the scaling procedures verify the basic assumptions applied by Sachs in formulating the scaling laws. (See Part A of the Appendix section of this report for a brief discussion of the relevant blast wave parameters formulated in terms of the Sachs' scaling relationships).

The compilation of blast data presented by Moulton[13] incorporates both HE (TNT and Pentolite) and nuclear blast phenomena. The HE data presented in this reference have been extracted from various sources; the data of Weibull[4] is used to illustrate overpressure functions; Fisher's and Pittman's[6] results have been used to illustrate the impulse functions resulting from detonation of TNT charges, and the data of Granström[14] has been used to illustrate shock duration time parameters and characteristics of the negative pressure region. This extensive, three volume report is, at the present time, undergoing revision and updating.

The report by Groves[15] describes a technique of determining the blast induced overpressures from distance-time observations of the motion of the shock front. Included with the overpressure data of this report is an estimate of the percent error of the various measurements. Over a range of peak overpressures from approximately 3 psi to 150 psi, the percent error associated with this set of measurements is less than 3%.

The report by Dewey[16] describes a method of determining the particle velocities associated with a blast event that employs high speed photography of smoke trails formed close to the charge just before detonation. The displacement with time of the smoke trails can be measured from the film record and the velocity of the smoke calculated. Analysis of these results gives the particle velocity-time history. The two 5 ton TNT denotations used in these tests were also analyzed to provide reflection factors of 1.70 and 1.88. However, the same test data as analyzed by Groves[17] indicates reflection coefficients of 1.76 and 1.60 respectively. Unfortuantely, these two references do not clearly describe the data reduction techniques used to achieve the quoted reflection coefficient magnitudes, hence, no judgement can be made regarding the correctness of either report. Groves compares the measured TNT data with the theoretical predictions of Brode[3] in terms of reflection coefficients, with the result that Brode's overpressure predictions appear low for large scaled distances. A similar conclusion is reached by Baker[1] when comparing the Pentolite data of Goodman[2] with the theoretical predictions of Brode[3].

The 100 ton TNT detonation test discussed in reference 18 involved the use of a hemispherical charge placed on the ground surface and was designed to provide measurements of surface and sub-surface blast phenomena and to study effects of blast on various targets and in tunnels and underground chambers. The 20 ton TNT detonation test results presented in reference 19 were designed to resolve small, but consistent discrepancies that appeared in previous tests and data collection programs. Complete discussions of the various types of instrumentation used is given in addition to tabular and graphical forms of data presentation. The summary report by Dewey[20] is not very useful, since this reference was merely designed for presentation at a technical meeting. However, this report indicates that peak air velocities determined by the smoke trail technique for 8 to 100 lb spherical charges of TNT agree quite well with the predicted, or expected velocities. The duration of the positive pressure phase is greater than expected (compared to Brode's[3] theoretical analyses). The discussion of a β ray absorption technique used to determine the time history of the air density in the blast field is perhaps the most interesting part of this reference.

Although the report of Shear and Wright[21] is primarily theoretical in approach, it does present experimental-theoretical correlation data (for peak overpressure) based on the experimental data of Goodman[2], Fisher and Pittman[6], and reference 19. The two reports by Rudlin[22,23] contain discussions of the basic physics of the explosive process during the early stages of the detonation wave and subsequent airshock phase. The photographic data obtained for the very early times in the detonation process is intended to represent the first in a series of efforts to gain knowledge of the basic physical characteristics of the detonation-shock wave formation process. The primary objective of the experiments was to examine the validity of Sachs' scaling procedures under the assumption that the airshock is independent of the explosive details. The density of the TNT charges was varied from a density of 1.01 gm/cc (loose powder) to 1.625 gm/cc (cast TNT) with the result that, at least, the airshock pressures were independent of charge density and dependent only on the energy released by the detonation. Kingery[24] has prepared a report that is primarily intended to cover the administrative and gross technical information for the forthcoming "Operation Snowball". However, this report does include tabular and graphical data of predicted overpressure, impulse, positive duration, arrival time, and dynamic pressure versus distance for 500 ton TNT surface detonation, as extracted from the data of references 18 and 19.

The report by Fisher[25] presents overpressure and impulse measurements from detonations of bare spherical cast TNT charges 6.5 inches in diameter weighing approximately 7.85 lb. These measurements are compared, with excellent agreement, to the experimental peak pressure-distance measurements by Stoner and Bleakney[26] and with the theoretical pressure-distance curve for cast TNT generated by Kirkwood and Brinkley[27]. Since the data of Stoner and Bleakney was obtained from denotation of Pentolite charges, the comparison made by Fisher in this report involves the computation of the magnitude of the factor required to convert from a TNT to Pentolite base. For scaled distances ranging from 4.5 to 11, Fisher finds that the weight of a TNT charge required to produce the same overpressure at the same scaled distance as generated by a Pentolite charge varies from 1.09 to 1.25. As noted previously, Baker[1] recommends a magnitude of 1.1 for this conversion factor. In addition, Fisher compares the peak overpressure computed from knowledge of the shock velocity using the Rankine-Hugoniot equation for ideal gases* with the measured peak overpressures, again with reasonably good agreement.

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* See Part B of the Appendix section of this report for a summary discussion of the Rankine-Hugoniot relationships.

Reference 28 discusses in several sections the methods employed to determine various blast wave parameters from a 100 Ton TNT detonation in August 1961 at the Suffield Experimental Station blast testing site. Unfortunately, no resultant data are given in this report. However, the report by Kingery, et al[29] presents overpressure, impulse, duration, arrival time, and dynamic pressure data measured during the same test. These data are compared to predicted curves with very good agreement. Since no ground reflection factors are given in this report, the reported data can not be used to provide a set of "free-air" blast parameters. However, once such a set of free-air data is determined from other sources, the data reported by Kingery et al can then be used to determine the ground reflection coefficient(s) applicable, at least, over the range of scaled distances ($1.67 \leq Z \leq 46.4$ ft/lb $^{1/3}$) and type of terrain covered in this 100 ton detonation.

The data to be presented by Rustanik and Lewis[30] in a forthcoming publication was collected during a series of tests designed to evaluate the effects of a blast environment on moving airfoils. The results of these tests were obtained from a set of carefully calibrated, fast response measuring and data recording instrumentation. A scaled distance range of 5-15 $\frac{ft}{(lb)^{1/3}}$ was covered by this series of eight data collection runs. Overpressure, duration, and arrival time were obtained from these tests, in addition to data concerning the response of the test series of airfoils.

The report by Fisher[31] is presented here primarily to incorporate the reflection coefficient data presented in reference 31 in this study. Fisher's results indicate that the measured, average reflection coefficients varied from 1.85 for a hard clay surface, to 1.99 for a perfect reflector simulated by the intersection of shock fronts from two identical spherical charges fired simultaneously. The tabulated results in reference 31 are presented as functions of the scaled height of the charge above the ground. The overpressure, impulse, and duration data given in reference 32 are presented for a scaled distance range between approximately 1.5 $ft/lb^{1/3}$ to 22 $ft/lb^{1/3}$. Unfortunately, the ambient pressure and temperature are not given in this reference. As noted previously, without these ambient conditions the data can not be applied to the evaluation program discussed in this report.

The following table summarizes the information and blast wave parameter data to be found in the data reference sources that have been discussed in this section. A definition of the symbols used in this table follows the table.

TABLE I - SUMMARY OF AIR BLAST DATA AVAILABLE FROM REFERENCES

Reference	Type of Explosive	Ambient Conditions P_o (psi)	Ambient Conditions T_o (^oK)	Range of Scaled Distance Covered by Data Z ($ft/lb^{1/3}$)	Type of Blast Wave Property Available From Data (symbols defined on following page) ΔP_s	ΔP_r	I_s	I_r	u_s	U	Δt	t	$\Delta p(t)$	u(t)	$\rho(t)$
1	Pent	14.7	300	3-60	x	x			x	x	x	x	x	x	x
2	Pent	14.7	300	.1323-66	x	x	x	x			x	x			
4	TNT	14.3-14.7	275-294	.396-47.4						x	x	x			
5	TNT	12.6	-	2.08-39.6	x		x				x	x			
6	TNT	-	-	3-20	x		x								
7	Pent	14.7	300	10.2-46.0	x		x								
9	Pent	-	-	1.48-14.81	x	x	x	x			x				
10	Pent	.39-.16	Amb	.5-2.0				x							
12	Pent	15-0.61	300-216	6-26	x		x				x				
13	Pent TNT	-	-	Variety	x		x		x	x	x	x			
15	TNT	variable	-	3-30	x										
16	TNT	-	-	4.12-5.2	x				x		x				

TABLE I (Continued), SUMMARY OF AIR BLAST DATA AVAILABLE FROM REFERENCES

Reference	Type of Explosive	Ambient Conditions P_o (psi)	Ambient Conditions T_o (°K)	Range of Scaled Distance Covered by Data Z ($ft/lb^{1/3}$)	ΔP_s	ΔP_r	I_s	I_r	u_s	U	Δt	t'	$\Delta p(t)$	u(t)	ρ(t)
17	TNT	13.57 13.69	272 310	4-70	x							x			
18	TNT	13.67	306	1.67-46.7	x						x	x			
19	TNT	13.54	300	2.4-60	x		x				x	x			
20	TNT	-	-	-							x				x
21	TNT Pent	-	-	2-40	x										
22	Pent	-	-	-	x					x					
23	TNT	11.91	-	3-18	x										
24	TNT	13.67	-	-	x		x				x	x			
25	TNT	14.7	-	1.70-12.75	*x		x								
28	TNT	13.67	305	—											
29	TNT	13.67	305	1.67-46.4	x		x				x	x			
30	TNT Pent	Variable		5.54-15.7	x						x	x			

DEFINITION OF SYMBOLS APPLIED IN TABLE I

Symbol	Definition	Typical Units
P_o	Ambient Pressure	psi
T_o	Ambient Temperature	^oK (or ^oR)
$Z = R/W^{1/3}$	Scaled Distance	$ft/lb^{1/3}$
R	Distance From Charge Center	ft
W	Effective Free-Air Weight of Charge	lb
ΔP_s	Peak Side-On Overpressure	psi
ΔP_r	Peak Reflected Overpressure	psi
I_s	Peak Side-On Positive Impulse	psi-msec
I_r	Peak Reflected Positive Impulse	psi-msec
u_s	Particle Velocity	fps
U	Shock Velocity	fps
Δt	Positive Duration of Overpressure	msec
t	Shock Arrival Time	msec
$\Delta p(t)$	Time History of Overpressure	psi
$u(t)$	Time History of Particle Velocity	fps
$\rho(t)$	Time History Density	$\frac{slugs}{ft^3}$, (or lb/ft^3)

B. Evaluation of Available Data Sources

1. General Comments

In general any reference that provides information on the blast parameters associated with the detonation of an explosive charge, as exemplified by the data sources discussed in Part A of this section, does not provide complete data unless the ambient pressure and temperature (or equivalent ambient sound speed) conditions under which the data was collected are specified. Without knowledge of these ambient conditions the scaled blast parameter relationships, summarized in Part A of the Appendix section of this report, can not be computed. Direct comparison of the blast data from various sources can not be accomplished without first reducing all data to a consistent set of environmental conditions, as provided by the Sachs' scaling relationships. Hence, of all the data sources discussed in Part A of this section, only those that define the magnitude of these ambient conditions will prove useful in the later sections of this report.

In addition, many of the data sources consulted during preparation of this report do not report "free-air" blast parameter data; i.e., these references provide data that incorporates an unknown (since it is unreported) ground reflection coefficient. Such data are not adequate for use in defining a consistant set of free-air blast parameter data; however, they are useful in establishing the magnitudes of the ground reflection coefficients once the free-air blast characteristics have been defined from other sources that provide direct, free-air data. Of those data sources that provide free-air blast characteristics, it has been noted that the majority of the experimental over-pressure and shock arrival time data extracted from the various source references tend to agree with one another quite well. Unfortunately, this is not the case with respect to positive phase duration time data. (The data of Ruetenik and Lewis[30] is probably the best source of internally consistent duration time data, at least over the scaled distance range from $Z = 5$ ft/lb $^{1/3}$ to $Z = 15$ ft/lb $^{1/3}$). Positive phase duration time data is the critical information needed to generate a set of self-consistent blast characteristics, since the resultant character of the particle velocity and density time-histories will be dependent, to a large extent, upon the correlation between the theoretically computed and experimentally measured overpressure time history characteristics.

Finally, since a self-consistent set of blast parameters resulting from Pentolite detonations has been presented by Baker and Schumann[1], the primary emphasis of this report has been directed toward providing a similar set of parameters for TNT detonations. Hence, the remainder of this section will be limited to a specific evaluation of the TNT data sources summarized in Table I, Part A of this section.

2. Evaluation of Specific Data Sources for TNT Detonations

The experimental data reported by Weibull[4] has been used in the latter sections of this report to provide a segment of the experimentally determined blast field parameters. It is to be noted that the Rankine-Hugoniot conditions and the data of Shear and Day[33]* were applied to Weibull's reported data in order to determine the magnitudes of the shock front overpressure functions.

As previously noted, the overpressure data reported by Doll and Salmon[5] does not agree with other overpressure data. This is probably due to the limiting response-time characteristics of the measuring instrumentation employed in reference 5. The data presented in reference 6 is also applied in this study, since it is in reasonable agreement with other similar data. It is to be noted that an ambient pressure of 14.7 psi was assumed for purposes of scaling these data.

Although the data sheets presented in reference 8 do not illustrate actual experimental data points, the curves drawn in this reference were used in the preliminary stages of plotting the final curves given in this report. This was done merely to insure that the general trend of the experimental data, and of the theoretical calculations, did not deviate by large orders of magnitude from the predictions given in reference 8.

The various curves presented in reference 13 are, as noted previously, based on the experimental data reported by Weibull[4] and Fisher and Pittman[6]. Hence, implicit use of the data contained in reference 13 has been

* The Rankine-Hugoniot conditions are valid only if the strength of the shock is not sufficient to induce dissociation. Above overpressures of approximately 4.5 atmospheres, the data of reference 33 which accounts for dissociation effects should be used.

accomplished in this study. In addition, the duration data of Granström[14] illustrated in reference 13 has also been applied in this study.

The data reported by Groves[15], and amplified in reference 17 has also been found to be applicable in this study. However, the same duration data reported by Dewey[16] appear too high by approximately a factor of two. In addition, the ground reflection coefficients in reference 16 do not agree with those of reference 15 (or equivalently, reference 17). The data reported in reference 18 is not applicable to the study discussed in this report. The data given in reference 19 is for a ground burst detonation. Unfortunately, no ground reflection coefficients are defined in reference 19; hence, these data can not be used to define the free-air characteristics of a TNT detonation. However, once the experimental overpressure-scaled distance relationship had been established from the data of references 6, 17, and 25, reflection coefficients were computed to effect agreement between the plotted data and that of reference 19. The duration and arrival time data of reference 19 were then modified by these reflection factors and applied to the appropriate "free-air" time-scaled distance plots in order to more completely define these blast parameters.

As noted previously, the limited data given by Dewey[20] is not in a form that lends itself to application to the manner of presenting the data given in this report. The data illustrated by Sheer and Wright[21] has been obtained from references 6 and 19, and has therefore formed a part of the data used in this study.

The data presented by Rudlin[22,23] is outside the region of interest in this study (reference 22) and can not be satisfactorily extracted from reference 23 because of interpolation difficulties that arise due to the manner in which the data are reported. The curves illustrated by Kingery[24] are not applicable to determination of the free-air blast environment, since no ground reflection coefficients are defined in this reference. The overpressure data reported by Fisher[25] is applicable to this study and has been used. The data given in reference 29 is for a ground burst and does not present ground reflection coefficient magnitudes. These data were used, however, in the same manner as previously discussed for reference 19. The data of Ruetenik and Lewis[30] are accompanied by reflection coefficient magnitudes and are therefore directly applicable to establishing the free-air blast characteristics of a TNT detonation*. The overpressure duration time data established in reference 30 do not exhibit as much scatter as do other duration data obtained from other sources. Unfortunately, the data of reference 30 only span a scaled distance range from approximately 5 to 15 ft/lb$^{1/3}$; hence, the theoretical-experimental comparisons evaluated in this report must rely on less reliable duration data outside the scaled distance range covered in reference 30.

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* The two Pentolite detonations included in these data agree quite well with the curves presented in Reference 1.

III. AIR BLAST PROPERTIES INFERRED FROM THEORY

We will discuss in this section the techniques employed by various investigators for analytical prediction of blast waves from conventional explosives. Because little work of this nature was published during the decade 1947-1957, we will first briefly consider the theoretical work accomplished prior to this time. We will next consider more recent (and more complete) predictions in some detail.

A. Theory Prior to 1947

Before World War II, essentially no theoretical predictions had been made of the characteristics of blast waves generated by any type of explosive source. Because of the need for such predictions during the war, intensive research was carried out in blast theory for both conventional and nuclear weapons, in more or less parallel efforts. The results of the early calculations for blast from nuclear weapons (the so-called Los Alamos "M Problem") are summarized by Fuchs in reference 34. Since these results do not strictly apply to the subject of this report, we merely mention them here for sake of completeness. The majority of the early theoretical predictions of air blast from conventional explosives were made by Kirkwood and Brinkley, in research conducted under sponsorship of the National Defense Research Council (NDRC). Their work is reported in a number of NDRC monthly progress reports, and in several summary reports[27, 35, 36]. Makino[37] has summarized the Kirkwood-Brinkley theory, and compared it with such experimental data as existed at the time of his report (1951).

From the Kirkwood-Brinkley theory, one can obtain predictions of peak overpressure, positive impulse, and positive phase duration for free-air bursts at sea level of spherical Pentolite and TNT, from the surface of the explosive charge out to scaled distances of slightly less than 30 $ft/lb^{1/3}$. [illegible] predictions can be made of time histories of various blast parameters, at either fixed or moving points in space.

B. Recent Computations

1. Brode's Theoretical Analyses

Brode[3,38,39,40,41] has developed a numerical technique for the solution of the flow parameters behind shocks which is applicable to a number of different cases. In general, the technique involves the use of Rankine-Hugoniot conditions in a numerical integration of finite difference equations. The difference equations are solved step by step and, in the limit of infinitesimal differences, converge to the exact differential equations of hydrodynamic flow in Lagrangian form. To avoid the difficulties which arise from the discontinuities in the flow parameters when traversing a shock, Brode employes the artificial viscosity technique developed by von Neumann and Richtmeyer[42]. The computational method can be applied to any problem involving the spherical flow of gasses behind a shock wave if one can formulate the equation of state for the gasses involved, and can determine the total blast energy released on initiation of the shock.

A detailed discussion of the problems Brode has solved using the above technique is presented below.

a. Point Source Explosion in an Ideal Gas (γ = 1.4)[38].

A point source explosion is one produced by the instantaneous release of energy from an infinitely small, concentrated source. It differs from the blast generated by the detonation of an explosive charge in that no high temperature, high pressure gases are generated, and the flow consists only of the propagation of a spherical shock wave into the surrounding medium. Brode has calculated this problem out to a shock overpressure of 0.1 atmosphere for an ideal gas with $\gamma = 1.4$. The results presented are peak overpressure, peak dynamic pressure and peak particle velocity as functions of shock radius; total pressure, particle velocity, and density as functions of Lagranian distance; overpressure, particle velocity, density and compression in units of their peak values as functions of Eulerian distance; duration of positive phases for pressure and particle velocity and positive and negative impulse as functions of Eulerian distance, and peak dynamic pressure as a function of time in units of positive duration of velocity. The significant feature of these results is their departure from the Taylor strong shock curves [43] at overpressures below 20 atmospheres.

b. Point Source Explosion in a Real Gas [39]

The solution to this problem is the same as that for the ideal gas case except that the calculatior employs the equation of state for a real gas (air). Computed values of the flow parameters are presented in the same format as before. Here the peak overpressure-distance curve lies below the same curve for the ideal gas case for shock pressures over 10 atmospheres. Thereafter the ideal gas assumption is reasonably valid.

c. Blast From an Isothermal Gas Sphere [40]

The gas dynamics arising from the sudden release of an initially static, high pressure, isothermal gas sphere are fundamentally different from those for a point source. However, the general computational method described before is also applicable in this case. Brode has carried out the computations for an ideal gas at three different initial conditions and compared the results with the point source solution. Two spheres were initially at 2000 and 121 atmospheres and high temperature (normal density) while the third, at 121 atmospheres initial pressure, had equal internal and external temperatures (high initial density). In this case the leading shock is strengthened as much as 20 percent after a period of time due to the effect of a second shock which overtakes the main shock. At increasing distances from the origin, the blast wave from an isothermal gas sphere begins to converge to the point source wave and the two will coincide (within 10 percent) after the shock wave has passed through a mass of gas 10 times as large as the initial mass in the sphere. Prior to this the shock strength is less than that of a point source shock.

d. Blast from a Spherical Charge of TNT[3]

In this case the numerical calculation uses the equation of state for TNT given by Jones and Miller,[44] and an equation of state for air determined by fitting a curve to the computed data of Gillmore,[45] and Hilsenrath and Becket.[46] Initial conditions for the problem are the detonation front conditions, as calculated by G. I. Taylor,[47] at the instant the front reaches the surface of a bare spherical charge of TNT having a loading density of 1.5 gm/cc. The air outside the blast front is taken to be at standard sea level conditions.

The results of the computations yield values for the common blast wave parameters both at the shock front and in the region behind the shock, extending back into the negative pressure phase. These results are presented graphically, and for peak overpressure versus distance they are compared with the theoretical results from Brodes earlier works for a point source explosion in air and in an ideal gas of $\gamma = 1.4$, and with Granström's[14] empirical curve for TNT at 1.52 gm/cc loading density.

It is specifically noted that the calculated results are valid only for bare spherical TNT of 1.5 gm/cc loading density detonated in a standard sea level atmosphere, and cannot be scaled to other atmospheric conditions without a simultaneous and proportional change in the charge loading density and detonation wave conditions. In addition, the results seem to lack internal consistency as evidenced by values of the same parameter that differ by more than 10% when read from different curves. Since the paper does not report results in tabular form, but only by means of graphs, it is not possible to determine whether this inconsistency is inherent in the calculations, or is due to careless plotting.

e. Spherical Shock Tube Blasts[41,48]

The numerical calculations are carried out for the explosion, in air, of glass filled spheres of air and helium at high pressure and density (ambient temperature). The computations and results are analogous to those of the isothermal sphere problem, but for real gasses, and are more characteristic of a high explosive blast than an ideal isothermal gas sphere.

2. Computations of Makino and Shear

Makino and Shear[49] have developed a computational technique to determine free air blast parameters behind the shock front based on known shock front parameters. The method involves the replacement of the hydrodynamic flow equations for the spherical flow of a non-conductive, non-viscous compressible fluid by a system of characteristic equations. The characteristic equations are written in finite difference form, using first differences only, and are then solved numerically. The initial conditions for the computation are the free air shock front parameters for spherical 50/50 Pentolite derived from Goodman's[4] fitted experimental curve and the Hugoniot equations. For scaled distances greater than Z = 19.8, the Kirkwood-Brinkley[35] asymptotic solution is used.

The authors have limited their computations to the flow region bounded by the shock front and the air-explosion gas interface, due to uncertanties about the equation of state for the explosion gases. For scaled distances greater than $Z \approx 2.04$, the computations are only carried back to a given characteristic curve due to computer limitations.

The results are presented in tabular form for the range of scaled distances $0.1323 \leq Z \leq 19.8$ and in graphical form for $0.1323 \leq Z \leq 1085$. However, the authors feel that the calculated results based on the Kirkwood-Brinkley asymptotic expansion are questionable, attributing the error to inherent deficiencies in the asymptotic formula

3. Naval Ordnance Laboratory Computations

The Air-Ground Explosions Division of the U. S. Naval Ordnance Laboratory has recently developed a computational technique to calculate all the blast wave parameters for 1 lb of TNT detonated in free air at sea level conditions.[50]

The most important new approach in this technique is the use of the Landau-Stanyukovitch equation of state for the detonation products of TNT.[23] This equation yields the correct Chapman-Jouguet conditions and also tends to an ideal gas with $\gamma = 1.24$ as the density decreases. For the region outside the zone containing the explosion gases, the program uses an appropriate equation of state for real air, based on the work of Hilsenrath.[51]

The program solves the one dimensional hydrodynamic equations of spherically symmetric flow using standard finite difference techniques. (Options are also included for problems involving plane and cylindrical symmetry.) Shocks are handled by the artificial viscosity method.

The calculations are carried out over the region extending from the leading shock wave back to the charge center. This region is divided into 300 zones which may be further divided among as many as 30 different regions or materials. A variable, internally calculated time step is also included. In order to reduce computing time, the program includes four types of rezoning.

The output subroutine prints tables of total pressure, specific volume, particle velocity, temperature, etc., versus distance at fixed times. Units are in the cgs system with pressure in megabars. The output can also be presented graphically if desired.

The subsequent sections of this study will use this computational technique as the theoretical basis for the comparison between theoretical predictions and experimental measurements of the blast parameters from free air detonations of TNT.

IV. COMPARISONS OF EXPERIMENT AND THEORY

A. Shock Front Parameters

The free air blast shock front parameters computed by the NOL "Wundy 75" Code described in Section III.B.3. were compared with compiled experimental data extracted from the various sources discussed in Sections II.A and II.B. A detailed discussion of the results of this comparison, and the correction factors applied to make the computed values fit the experimental data, is presented in the following paragraphs.

Since the artificial viscosity method used in the theoretical calculation of the shock front parameters tends to obscure the true position of the shock front, it was assumed that the instantaneous time-space position of the shock front coincided with the peak tabular value of overpressure given in the computer print-out sheets (see Figure 1). The shock arrival time determined by this approach was then plotted against scaled distance on log-log paper. Experimentally determined values of the arrival time were next plotted on the same sheet in order to determine how well the theoretically predicted values fit the experimental data. The results show that the theory is in excellent agreement with experiment when predicting shock arrival time, and no further correction is required.

This same correlation technique was then applied to the other shock front parameters ($\frac{\Delta P_s}{P_o}$, $\frac{u}{a_o}$ and $\frac{\rho}{\rho_o}$). In general, the theoretically predicted magnitudes of these parameters were significantly lower than experimental values at the same scaled distances, requiring the application of additional correction factors in order to bring the theory into agreement with experiment.

The necessary correction factors for each parameter were determined by computing the experimental to theoretical ratio for that parameter at discrete points over the range of scaled distances involved.

For example: $$C_{\Delta P_s, z} = \left.\frac{\Delta P_s \text{ exp}}{\Delta P_s \text{ theor.}}\right|_z$$

In general, the correction factors determined by this approach were essentially constant over rather large ranges of scaled distance. The values determined for the correction factors to be applied to the various shock front parameters are given in Table II.

Table II

Blast Wave Parameter Correction Factors

Parameter	C	Scaled distance where applicable
ΔP_s	1	$Z \leq 1$
	1.20	$Z > 1$
u_s	0.916	$Z < 1$
	1.078	$1 \leq Z \leq 5.1$
	1.165	$5.1 < Z$
ρ_s	1.089	$Z \leq 5$
	$1 + \frac{.5632}{Z^{1.146}}$	$5 \leq Z$

It should be noted that the so-called experimental values of peak particle velocity and peak density were calculated from the experimental data for peak overpressure using the tables given by Shear and Wright[21]. The shock velocity, which wes nor calculated by the SOL code, was determined from the corrected peak overpressure using the same tables.

Figure 1

OVERPRESSURE CORRECTION TECHNIQUE

t = const.

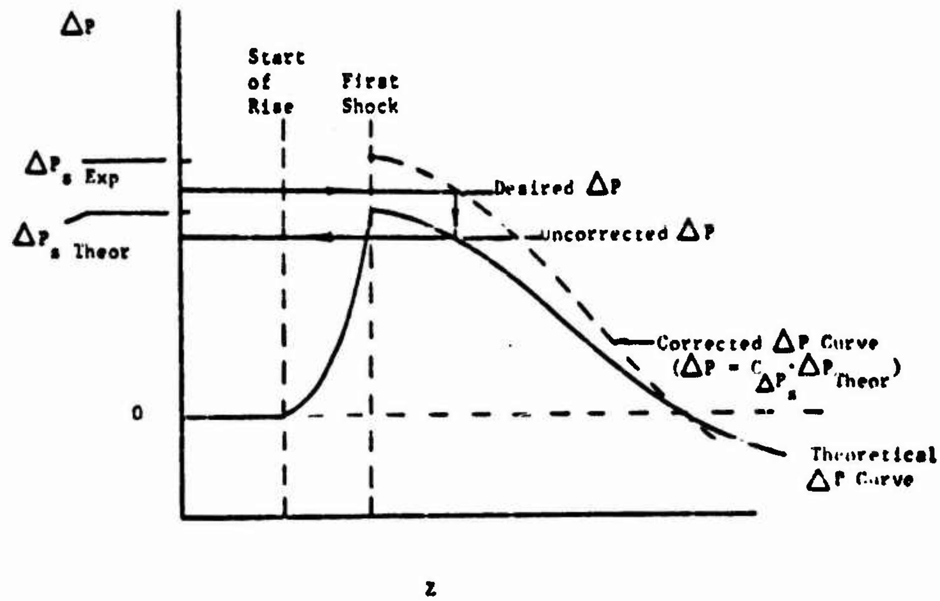
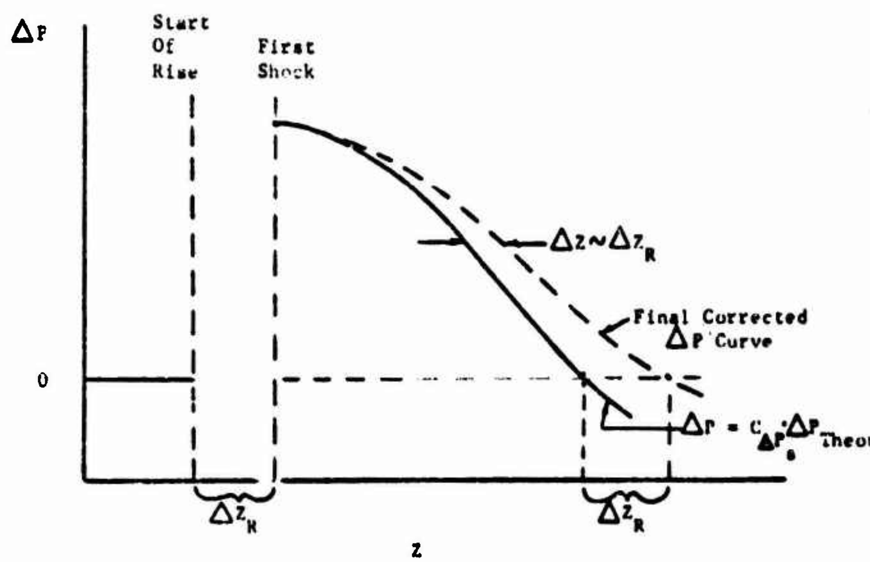


Figure 2

TIME CORRECTION TECHNIQUE

t = const.



B. Time Histories of Blast Parameters

The only experimental data available that will provide a comparison with theoretically computed time histories of the various blast parameters is the time duration of positive overpressure. This comparison was accomplished in a manner analogous to that used in part A of this section. The results showed that, if the theoretically predicted duration of positive phase, at a given scaled distance, was determined as the time from the start of rise in pressure ahead of the shock to the time the pressure again returned to the ambient condition, the theory and experiment were in satisfactory agreement for scaled distances less than 11.5 $ft/lb^{1/3}$. At larger scaled distances, this method tended to over estimate the duration of positive overpressure, requiring the application of an additional correction factor to the start of rise time.

The corrected time histories of overpressure were then obtained in the following manner: It was assumed that the correction factors determined in part A of this section also applied to overpressures behind the shock front. In order to plot lines of constant overpressure (corrected for pressure only) on a Z-t plot, the desired value of overpressure was divided by the appropriate correction factor, yielding the corresponding uncorrected value to be found in the computer output sheets. This is schematically shown in Figure 1. The Z and t values corresponding to given values of overpressure were then used to generate the lines of pressure-corrected constant overpressure on a Z-t plot. In addition, lines representing the first shock and start of rise of pressure were placed on the same plot. Corrected time histories of overpressure were then obtained by graphically shifting the start of rise curve in the Z direction to coincide with the first shock curve, and then shifting all curves behind the first shock the same amount in Z as the start of rise curve.

The corrected time histories of particle velocity (u/a_o) and density ratio (ρ/ρ_o) were then obtained in the same manner.

C. Ground Reflection Factors

The following table lists the reflection factor(s) either given in, or computed from the data of the specified reference. These ground reflection factors are the coefficients used to compute the effective free-air charge weight; i.e., the weight of charge required in the absence of a (ground) reflecting surface to generate a blast wave strength (overpressure) equivalent to that produced by a charge in the presence of a reflecting surface.

Table III

Ground Reflection Factors

Reference	Type of Surface	Reflection Factor
1	----	1.80
17	----	1.60 - 1.76
19	----	1.69
29	----	1.39
31	hard clay	1.85
"	perfect reflector	1.99
"	water	1.91

It is to be noted that only reference 31 clearly specifies the magnitude of the reflection coefficient as a function of the type of ground reflection surface. The data of Ruetenik[30] also presents reflection factors; however, the magnitudes of these factors indicate that a modified definition of this coefficient has been used in this reference.

D. TNT-Pentolite Conversion Factors

Table IV lists TNT to Pentolite conversion factors extracted from the sources cited in the first column. These conversion factors are simply the weight of TNT necessary to obtain the same overpressure, at a given distance, as obtained from the detonation of 1 lb of Pentolite.

Table IV

TNT-Pentolite Conversion Factors

Reference	Z (ft/lb$^{1/3}$)	Conversion Factor
1	---	1.1
25	4.5	1.09
"	5.0	1.13
"	6.0	1.18
"	7.0	1.22
"	9.0	1.25
"	11.0	1.25

A similar comparison between the experimental data for TNT used in this report and Goodman's[2] data for 50/50 Pentolite yielded the TNT to Pentolite conversion factors listed in Table V.

Table V

TNT-Pentolite Conversion Factors-This Report

Z	Conversion Factor
.460	1.20
.887	1.06
1.38	1.10

Table V (Continued)

Z	Conversion Factor
2.12	1.14
2.96	1.15
4.21	1.18
5.68	1.21
11.8	1.08
21.3	1.07
47.0	1.24

Based on these results, the correction factor of 1.1 given in reference 1 appears to be a reasonable average value.

V. PRESENTATION OF SELF-CONSISTENT DATA

This section presents large scale log-log plots of the self-consistent blast data generated by this study for one pound of TNT detonated in free air.

Figure 3 presents the shock front values of the various blast parameters as functions of scaled distance from the charge center.

Figures 4, 5, and 6 present space-time plots of overpressure, particle velocity and density, in that order.

These figures are to be found at the end of this report.

<u>Legend for Figures 3, 4, 5 and 6</u>

Symbols:

$\frac{\Delta p}{p_o}$ = side-on overpressure, atmospheres

$\frac{U}{a_o}$ = shock velocity, dimensionless

$\frac{u}{a_o}$ = particle velocity, dimensionless

$\frac{\rho}{\rho_o}$ = density, dimensionless

Z = scaled distance, $ft/lb^{1/3}$

$\frac{t\,\bar{a}}{(W/\bar{P})^{1/3}}$ = scaled time, $ms/lb^{1/3}$

$\frac{\Delta t\,\bar{a}}{(W/\bar{P})^{1/3}}$ = scaled positive duration, $ms/lb^{1/3}$

R = distance, ft

W = weight of TNT, lb

a = sonic velocity, ft/sec

$\bar{a}$ = $\frac{a_o}{1117}$

P = pressure, psi

$\bar{p} = \frac{P_o}{14.7}$

Subscripts:

s = shock front

o = ambient atmosphere

The line labeled interface on Figures 4, 5 and 6 designates the boundary separating air from explosion gas.

VI. DISCUSSION

In this report, we have presented a self-consistent set of blast wave properties that characterize the parameters associated with detonations of TNT explosive. This self-consistent set of blast wave properties has been generated from a marriage of the experimental data collected and recorded by various experimenters with the theoretical computational technique developed by personnel of the Air-Ground Explosions Division of the U. S. Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland. The details of this computational technique are described in reference 50. The experimentally determined data applied in the theoretical-experimental comparison study described in this report have been extracted primarily from references 4, 6, 17, 19, 25, 29, and 30. Other sources of experimental data and other theoretical analyses have been reviewed and discussed in this report primarily to provide an overall, comprehensive examination of the present state-of-the-art with respect to blast wave characteristics.

The graphical format used for presentation of the self-consistent set of TNT blast wave properties was chosen primarily to correspond to the format applied by Baker and Schuman[1] for a similar presentation of Pentolite properties. In addition, the scale of these graphs has been selected to provide three-place reading accuracy for the entire scaled distance range covered in these charts.

During the effort expended in this study that was concerned with evaluating the various sources of experimental data, it was clearly evident that the overpressures and arrival times measured by different experimenters tended to agree quite well. However, the duration time measurements were quite scattered, even for data extracted from a single reference. (As noted previously, the duration data obtained from reference 30 was the best of such data found during this study). It is suggested that future experimental blast wave detonation programs make an attempt to overcome the deficiencies now associated with duration time measurements. Moreover, it is suggested that in future detonation tests the measurement of ambient pressure and temperature be emphasized as being as important as the collection of the blast data itself. Much of the data found during this study could not be used due to the complete lack of such information.

The curves presented in this report are felt to represent the best fit of the NOL computational results to the existing experimental data. As such, these curves can be used to plan future experimental test programs, the data from which can then be used to verify the results illustrated in this report. As more such data becomes available, it may be evident that the curves presented in this report require adjustment and/or revision. To insure the continuing usefulness of this report, it is suggested that the curves presented in this report be updated as required by additional, future data. In addition, it is suggested that consideration be given to conducting a program similar to the one discussed in this report for Pentolite explosive. Although reference 1 presents similar data for Pentolite, these data are based on a marriage of Brode's[3] theoretical calculations for TNT with Goodman's[2] experimental data for Pentolite. Since the theoretical analysis[30] applied in this report appears to agree with experimental data better than the theory advanced by Brode[3], and since this analysis could be recomputed for Pentolite explosive, it would be worthwhile to compare Goodman's[2] data to this theoretical approach. Re-evaluation of the data presented in reference 1 would, it is believed, remove some of the inconsistencies apparent in the results of reference 1. In effect, this re-evaluation would provide a better basis of comparison of Pentolite and TNT detonations than is available at the present time.

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APPENDIX

A. Blast Parameters Based on Sachs' Scaling Laws

The ratios presented in this section define the relevant blast wave parameters formulated from analysis of the general laws of similitude originally proposed by Sachs[11] and experimentally verified by various experimenters (e.g. references 2, 6, 7, 9, 10, 12). Since there are various references that discuss the details of these scaling analyses, they will not be presented in this section. (The interested reader is refered in particular to the paper by Sperrazza[52] for derivations of the scaled blast wave parameters). Rather, this brief section will be limited to listing the form of these blast wave parameters as obtained from application of the general similitude relationships of Sachs that account for variations in ambient pressure, temperature, and size of charge.

Scaled Blast Parameter	Description	Typical Units
$\Delta P_s / \bar{p}$	Scaled Overpressure	psi
$\dfrac{I_s\ \bar{a}}{(W/\bar{p})^{1/3}\ \bar{p}}$	Scaled Impulse	psi-msec/lb$^{1/3}$
$\dfrac{R}{(W/\bar{p})^{1/3}} = Z$	Scaled Distance	ft/lb$^{1/3}$
$\dfrac{t_a\ \bar{a}}{(W/\bar{p})^{1/3}}$	Scaled Shock Arrival Time	msec/lb$^{1/3}$
$\dfrac{\Delta t\ \bar{a}}{(W/\bar{p})^{1/3}}$	Scaled Positive Duration Time	msec/lb$^{1/3}$

In this listing, in addition to the symbols defined in Table I of Section IIA of this report, the following symbols are defined:

$\bar{p} \equiv \frac{P_o}{14.7}$ Ratio of Ambient pressure to that at sea-level

$\bar{a} \equiv \frac{a_o}{1139}$ Ratio of ambient sound velocity to that at sea-level

It is to be noted that in both this listing and in Table I of Section II A the symbol W is used to denote the "effective free-air charge weight." By this is meant that for detonations close to the ground, the actual weight of the charge is to be multiplied by the ground reflection factor to account for the enhancement of the strength of the blast due to the presence of a ground (reflection) plane.

B. Rankine - Hugoniot Relationships

The basic relationships among the properties of a blast wave are derived from the Rankine-Hugoniot conditions based on the conservation of mass, energy, and momentum at the shock front. These conditions, together with the equation of state for air, permit the relationships between shock velocity, particle velocity, overpressure, dynamic pressure, and the density of the air behind the shock front to be derived. These relationships will be presented in this section without derivation, in order to provide the reader with expressions relating the various blast wave parameters that are applicable for, at least, shock front velocity - to - ambient sound speed ratios less than two (overpressures less than, approximately, 4.5 atmospheres)*. For those interested in the derivation and discussion of these relationships, reference to the texts edited by Glasstone[53] and authored by Courant and Friedricks[54] should be made. The following nomenclature listing defines the symbols used in the equations presented in this section.

Symbol	Definition
a_o	ambient sound speed (ahead of shock)
P_o	ambient pressure (ahead of shock)
q	peak dynamic pressure
u_s	particle velocity (behind shock)
ΔP_s	peak overpressure
ΔP_r	reflected overpressure
U	shock front velocity
ρ	density behind shock
ρ_o	ambient density (ahead of shock)

* See reference 33 for the technique to be applied in cases exceeding this limit.

The relevant equations relating these parameters are:

$$U = a_o\left(1 + \frac{6\Delta p_s}{7p_o}\right)^{1/2},$$

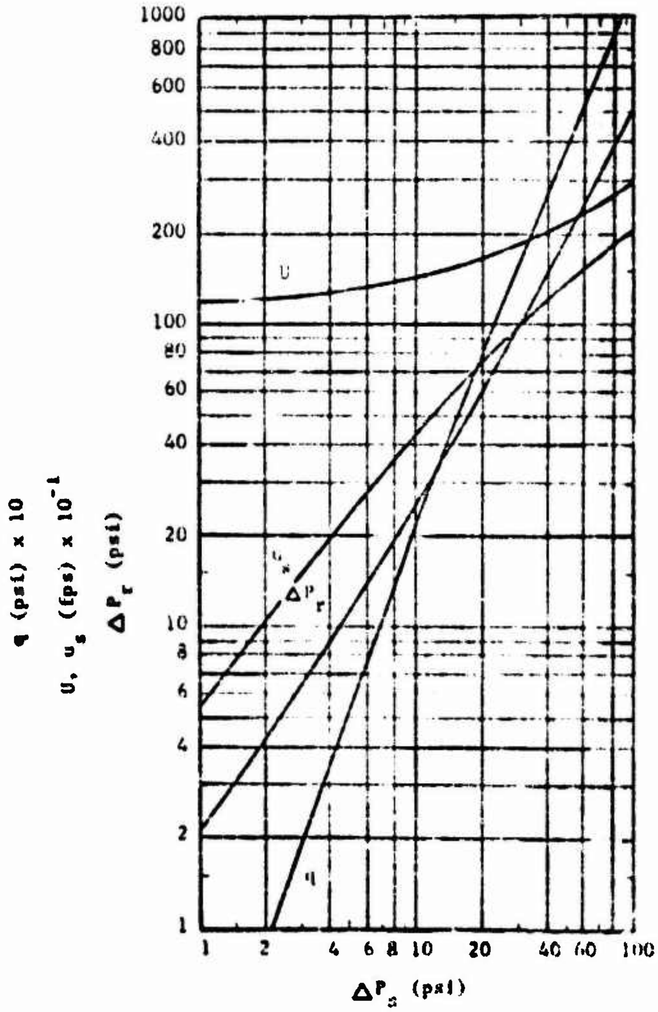
$$u_s = \frac{5\,\Delta p_s}{7\,p_o}\left(\frac{a_o}{\left(1 + \frac{6\Delta p_s}{7p_o}\right)^{1/2}}\right),$$

$$q = \frac{1}{2}\rho\, u_s^2 = \frac{5}{2}\,\frac{(\Delta p_s)^2}{7p_o + \Delta p_s},$$

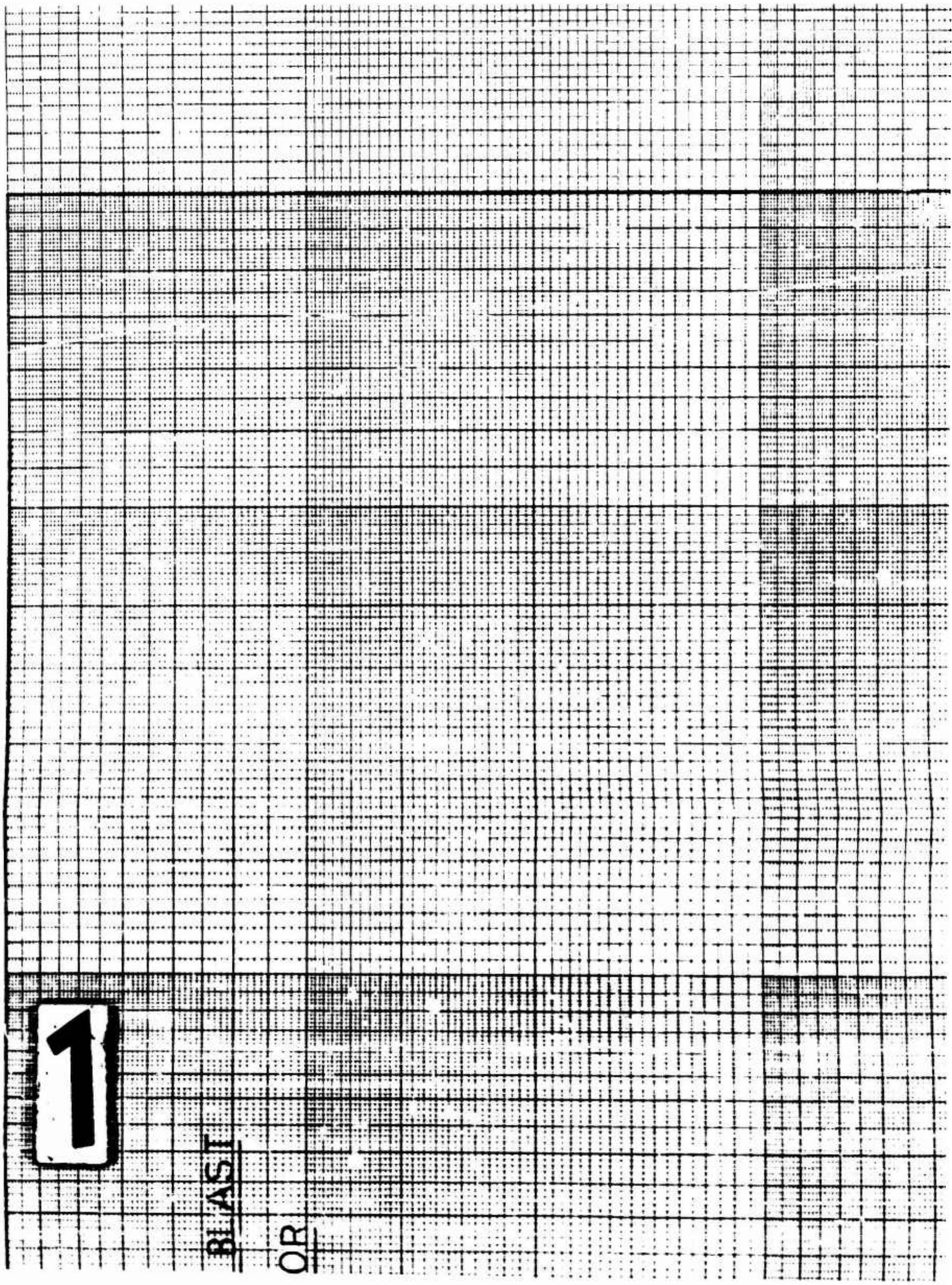
$$\rho = \rho_o\left(\frac{7 + \frac{6\Delta p_s}{p_o}}{7 + \frac{\Delta p_s}{p_o}}\right),$$

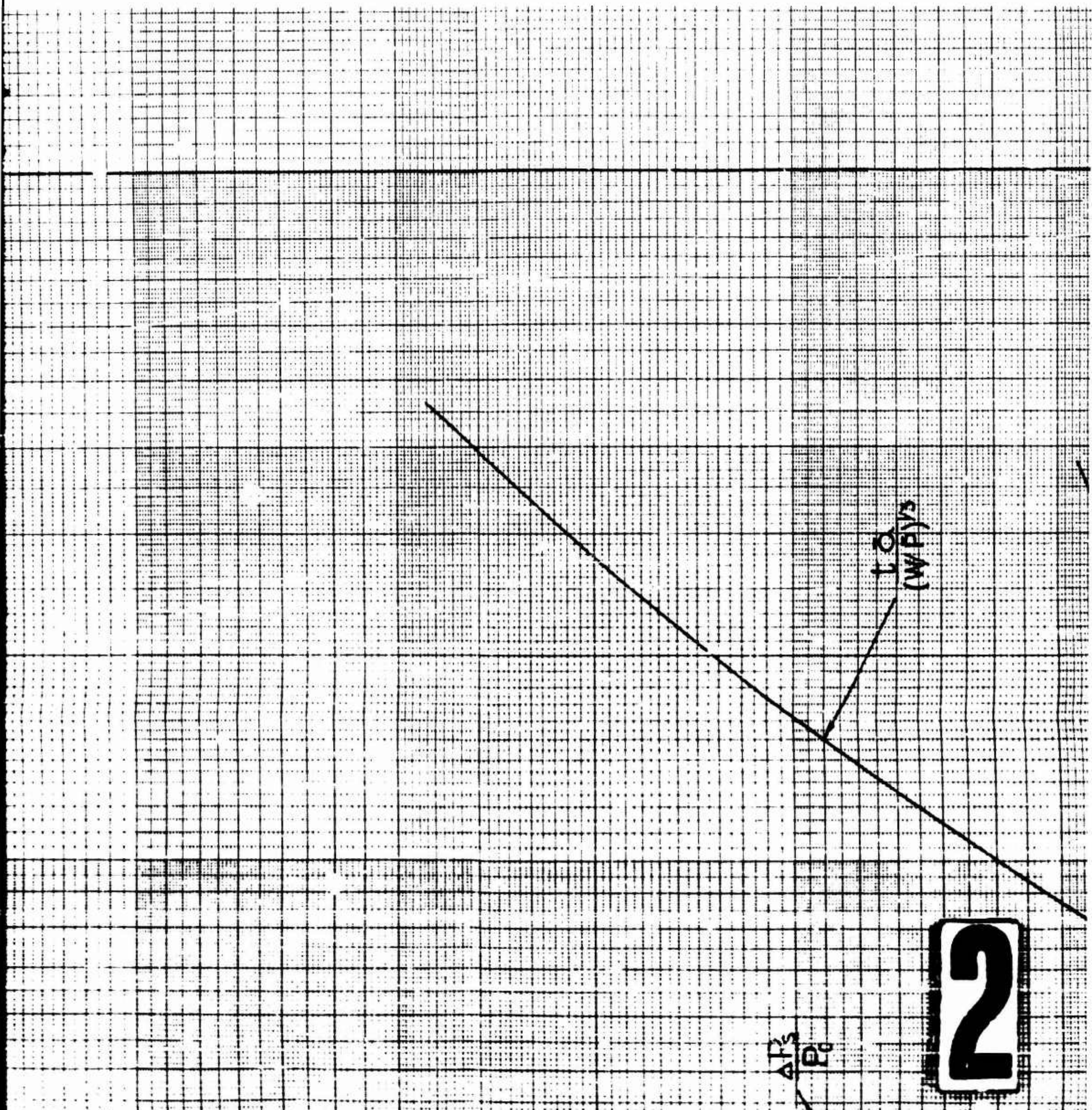
$$\Delta p_r = 2\Delta p_s\left(\frac{7p_o + 4\Delta p_s}{7p_o + \Delta p_s}\right)$$

The following curve has been extracted from Glasstone[53] (Figure 3.80) and is presented in this report in order to illustrate the character of these equations.

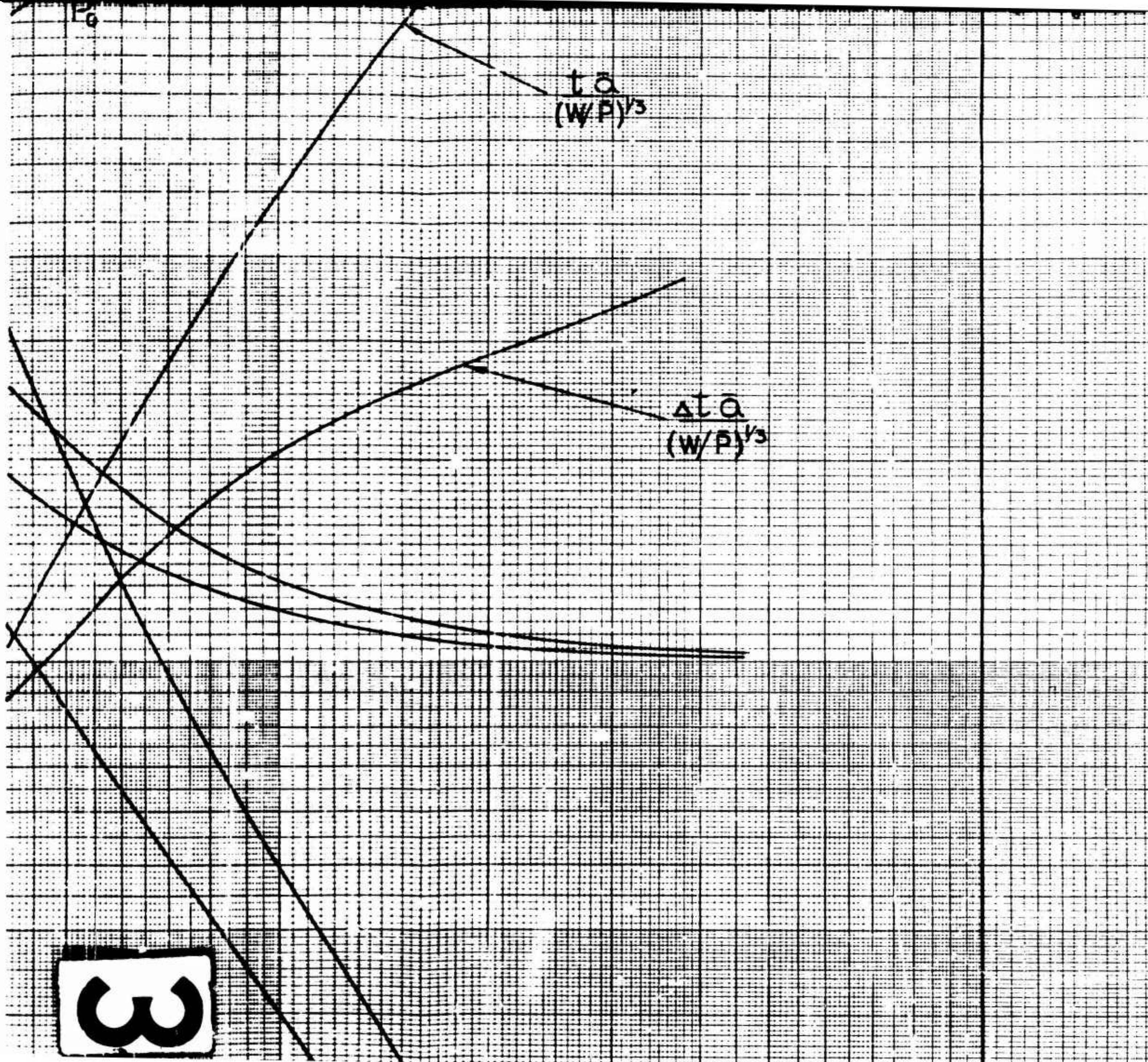


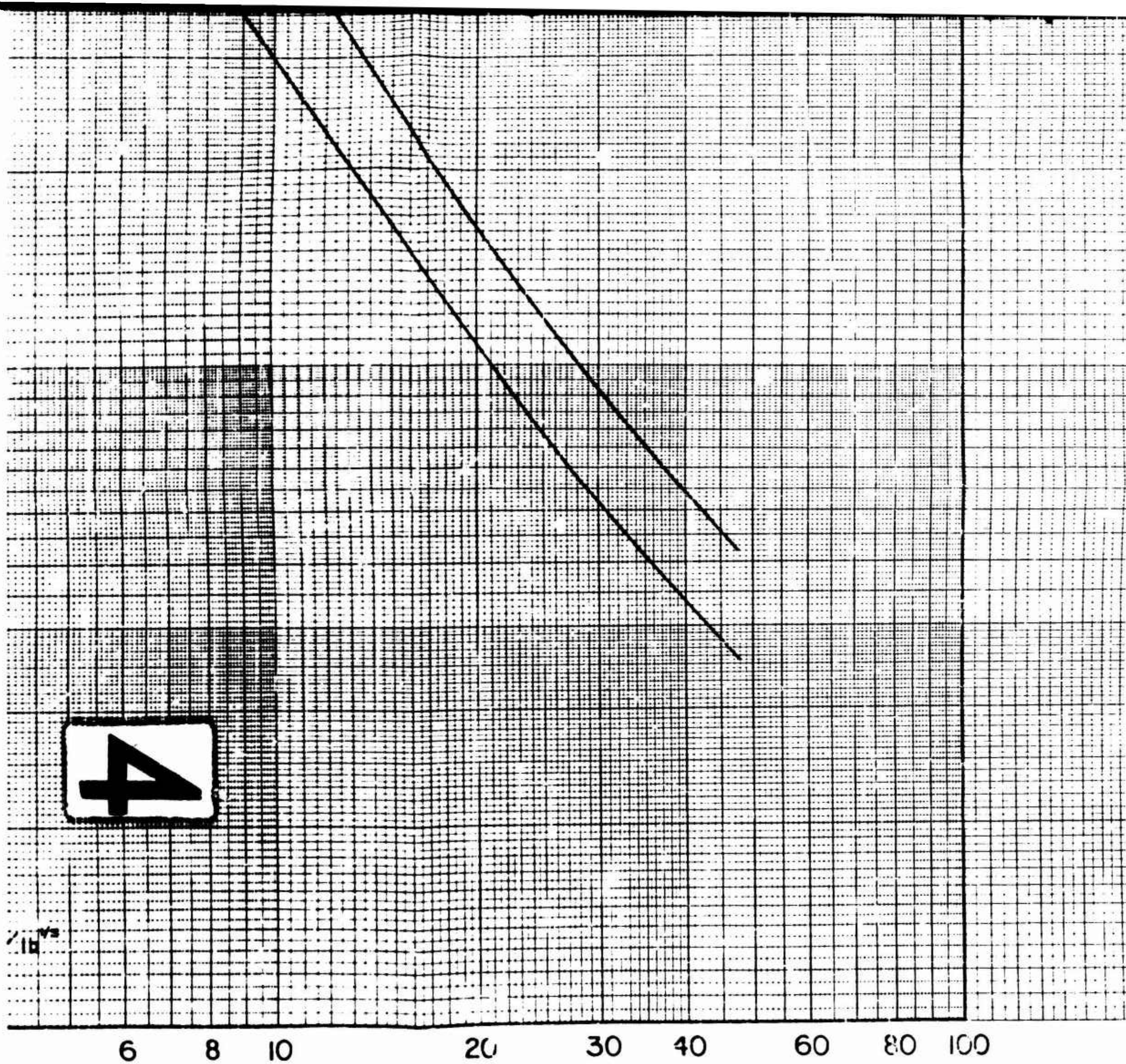
Relation of Blast Wave Parameters at the Shock Front to Peak Overpressure


1
BLAST
OR



$\frac{t_a}{(W P)^{1/3}}$
$\frac{\Delta P_s}{P_0}$
2


$\frac{t\,a}{(W/P)^{1/3}}$
$\frac{\Delta t\,a}{(W/P)^{1/3}}$
3


6
8
10
20
30
40
60
80
100
4

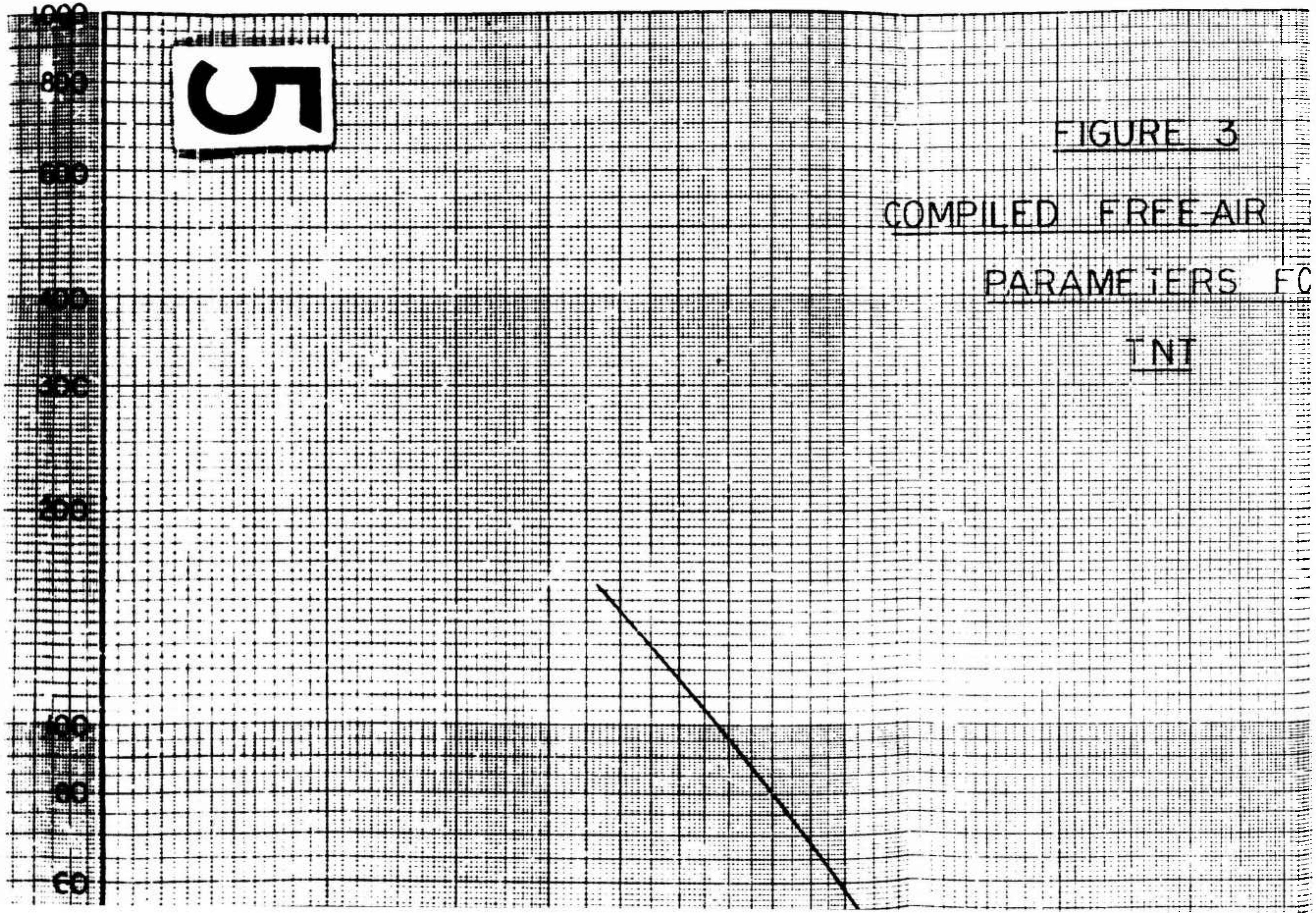
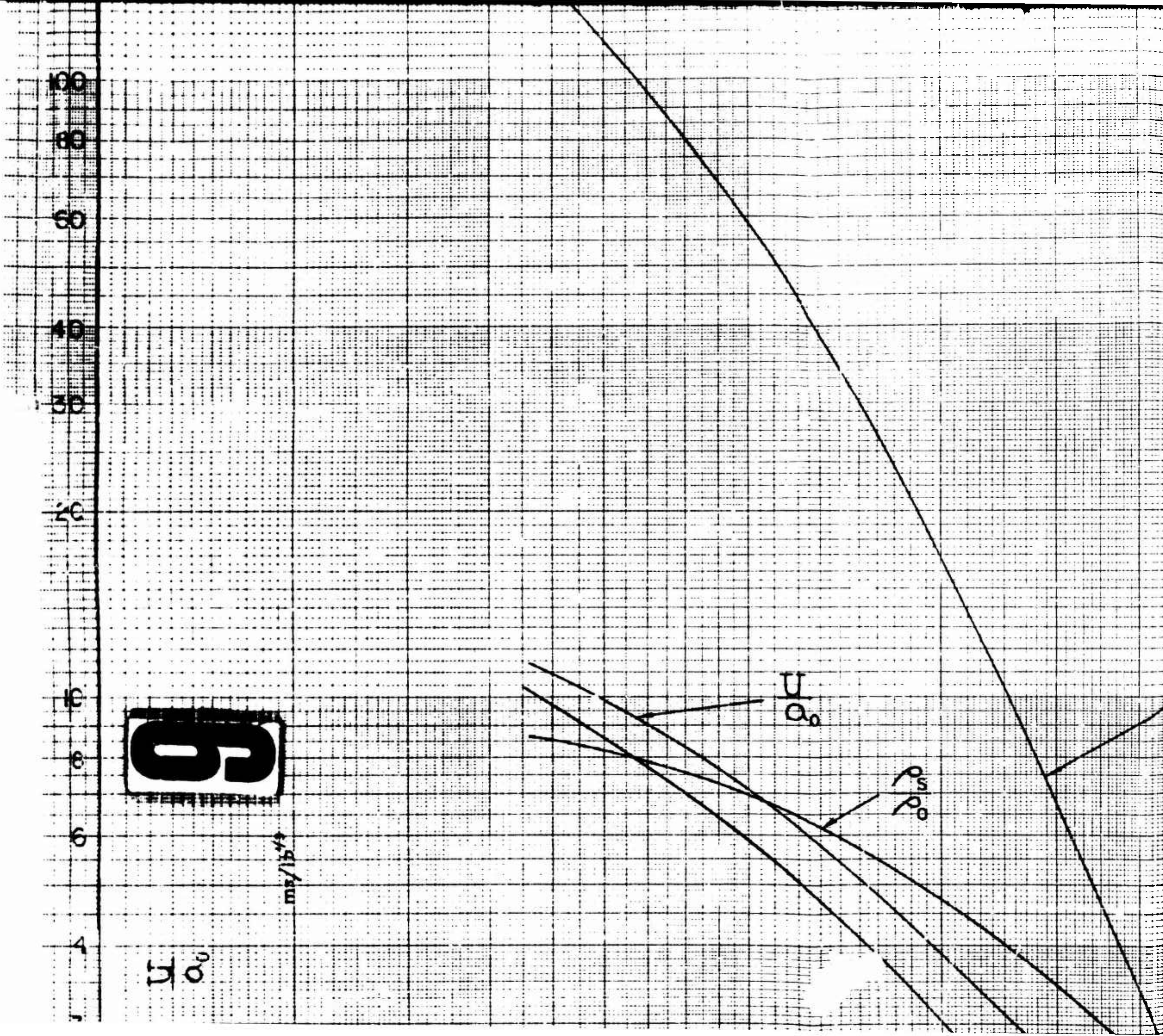


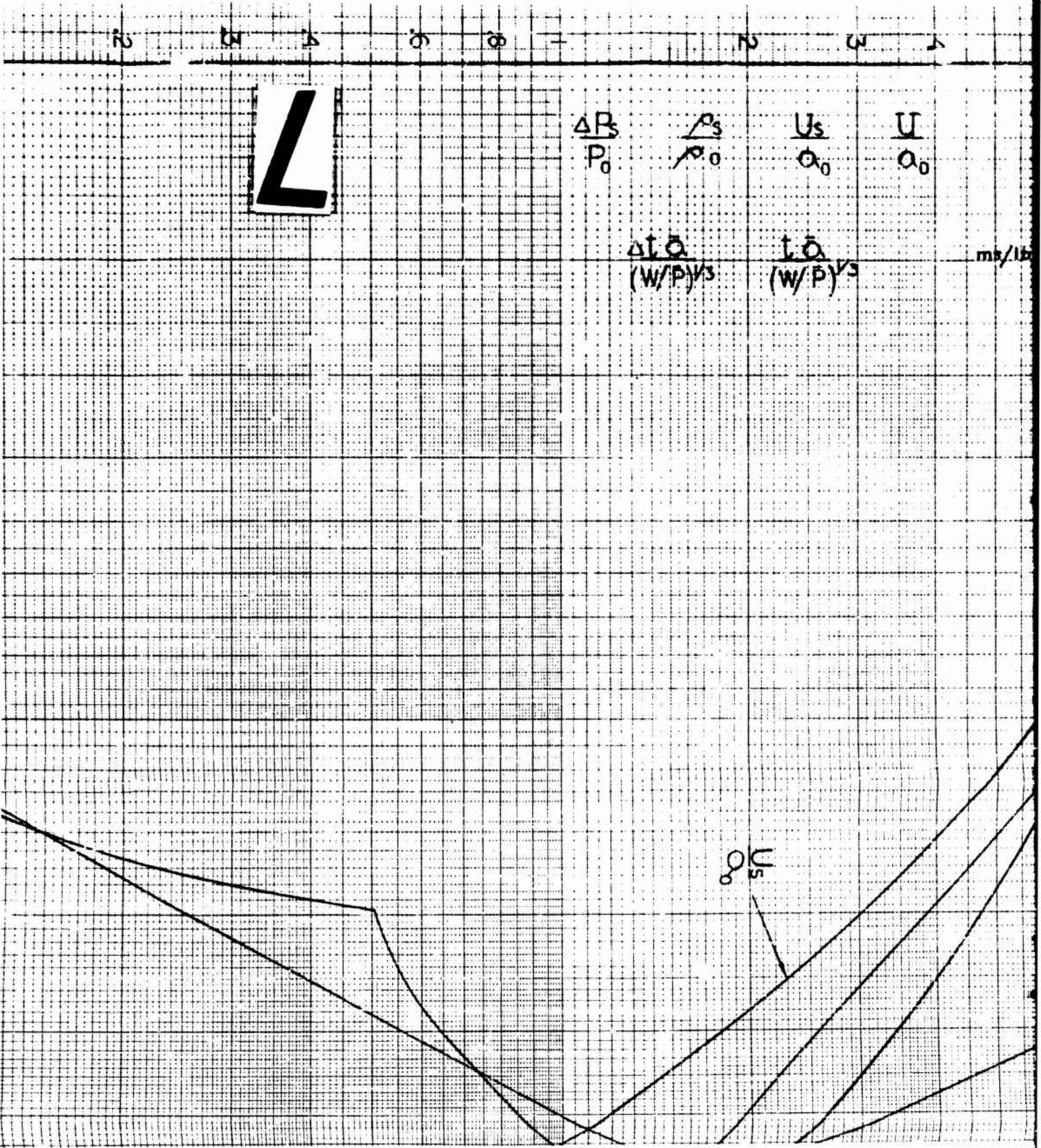
FIGURE 3

COMPILED FREE-AIR

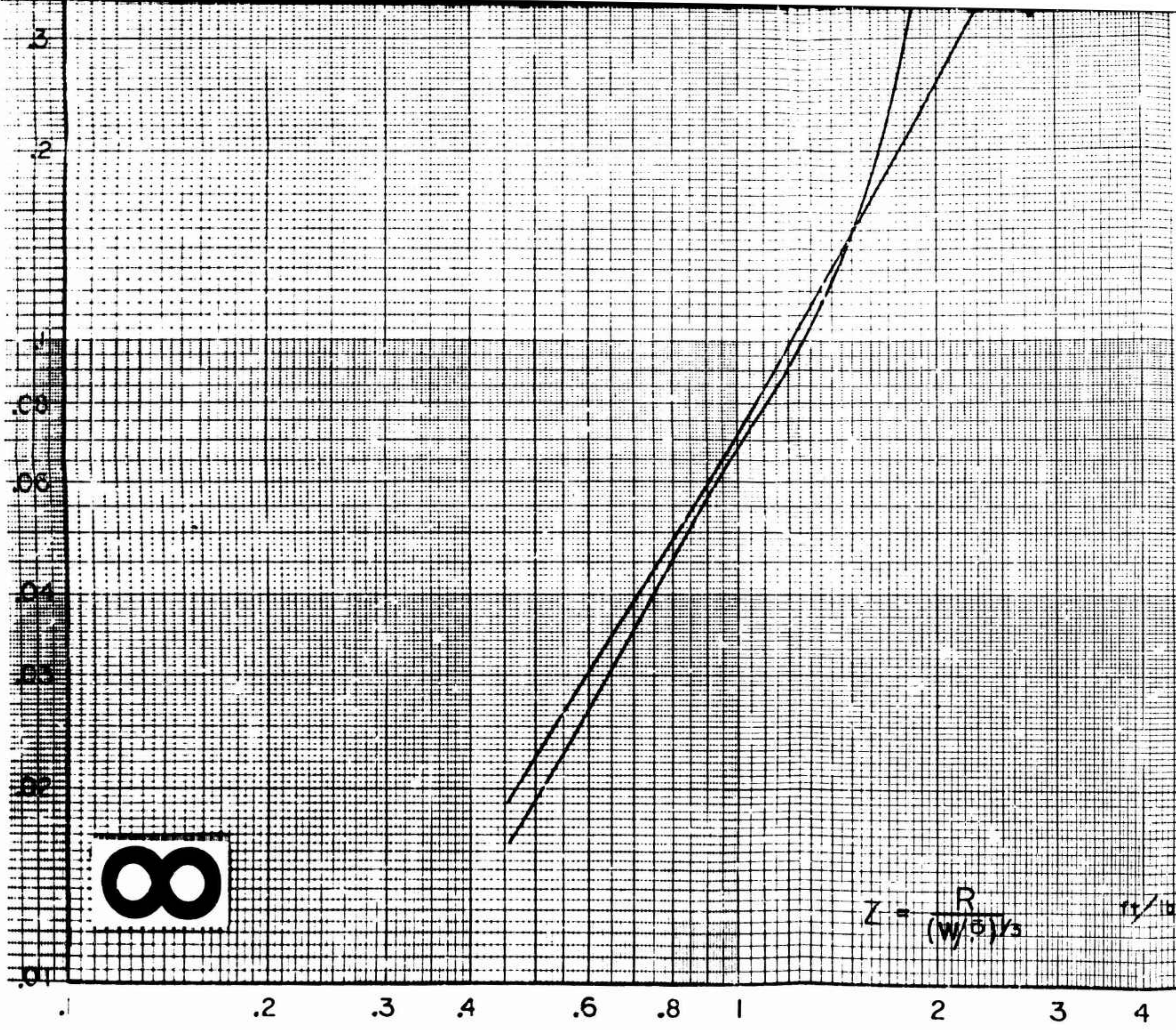
PARAMETERS FO

TNT


100
80
60
40
30
20
10
8
6
4
$\frac{U}{a_0}$
$\frac{\rho_s}{\rho_0}$
ms/lb^1/3
9



.2 .3 .4 .6 .8 1 2 3 4
7
$\frac{\Delta P_s}{P_0}$
$\frac{\rho_s}{\rho_0}$
$\frac{U_s}{a_0}$
$\frac{U}{a_0}$
$\frac{\Delta t\,\bar{a}}{(W/P)^{1/3}}$
$\frac{t\,\bar{a}}{(W/P)^{1/3}}$
ms/lb
$\frac{U_s}{a_0}$


.3
.2
.1
.08
.06
.04
.03
.02
.01
.1
.2
.3
.4
.6
.8
1
2
3
4
$Z = \frac{R}{(W/\delta)^{1/3}}$ ft/lb
8

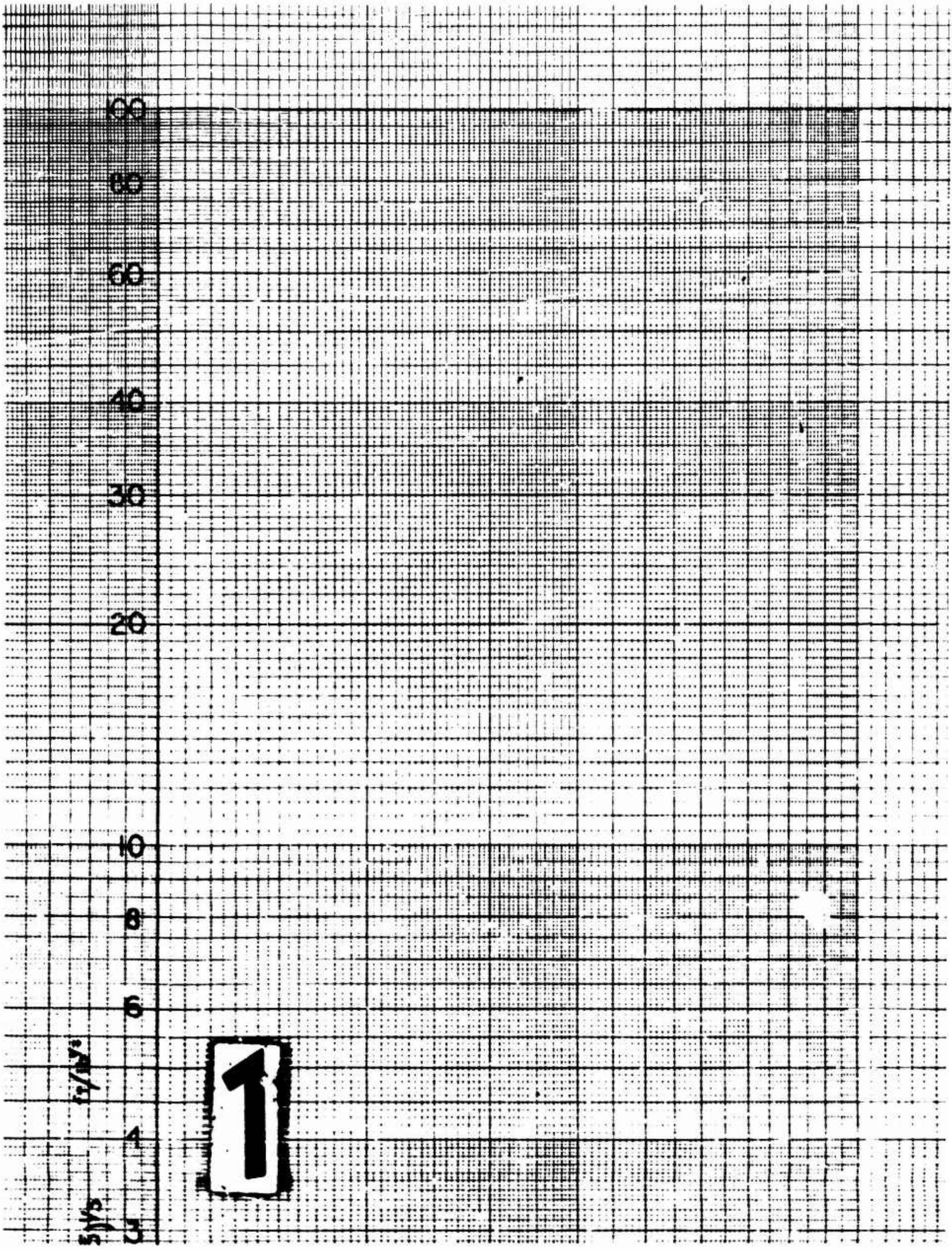

100
80
60
40
30
20
10
8
6
4
3
1

FIGURE 4

TIME HISTORIES OF OVERPRE

$\frac{\Delta P}{P_0}$

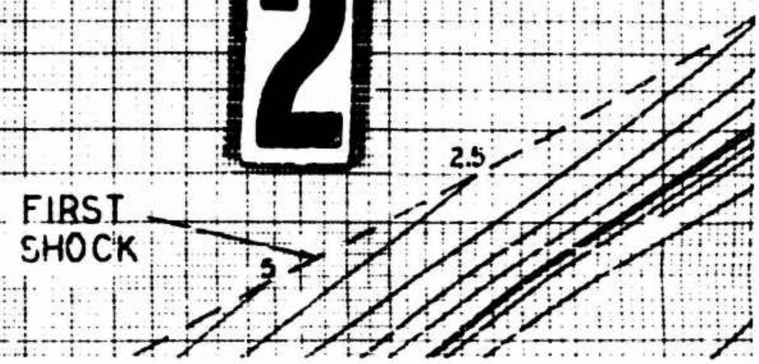


FIGURE 4

IORIES OF OVERPRESSURE

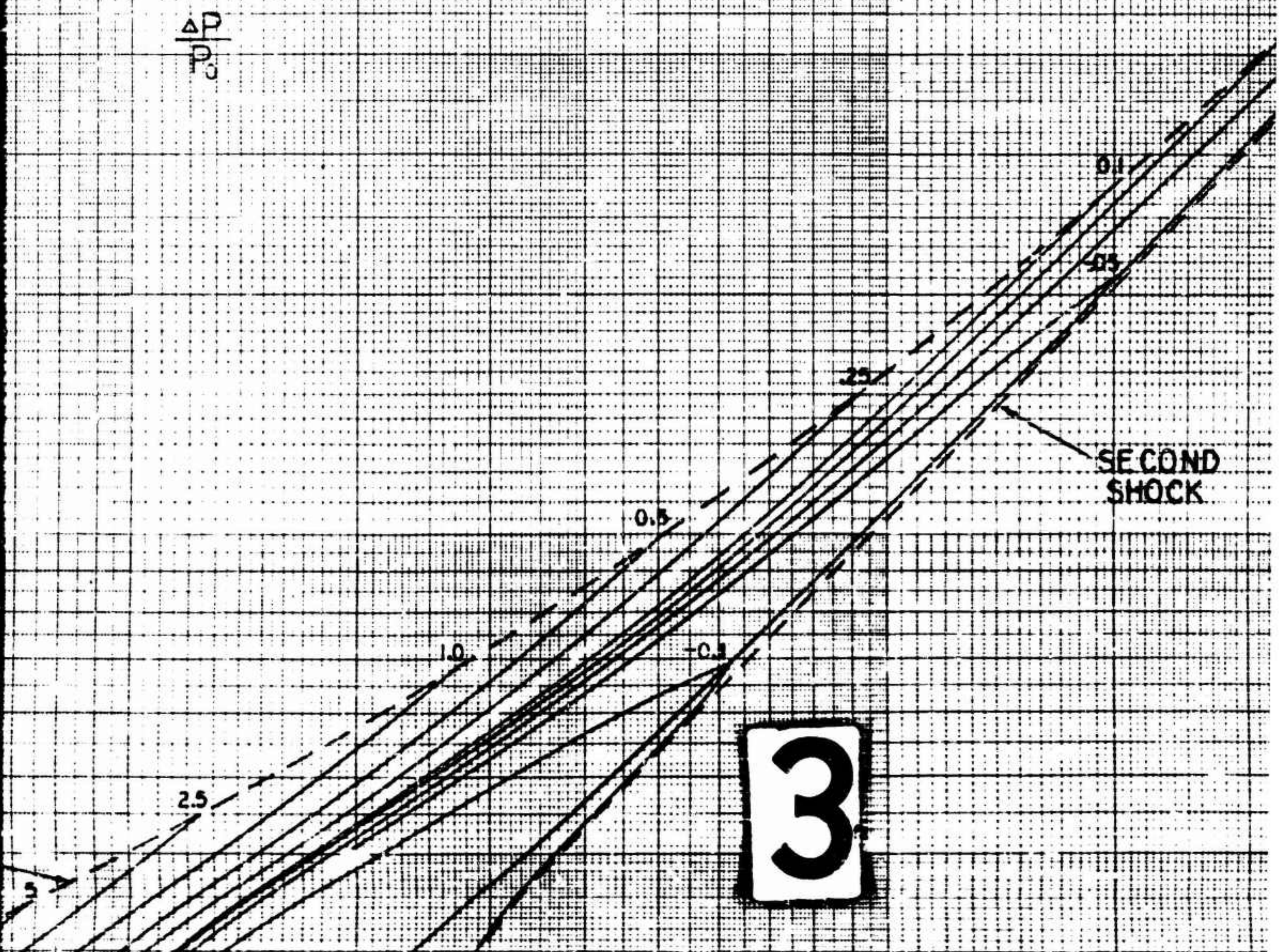
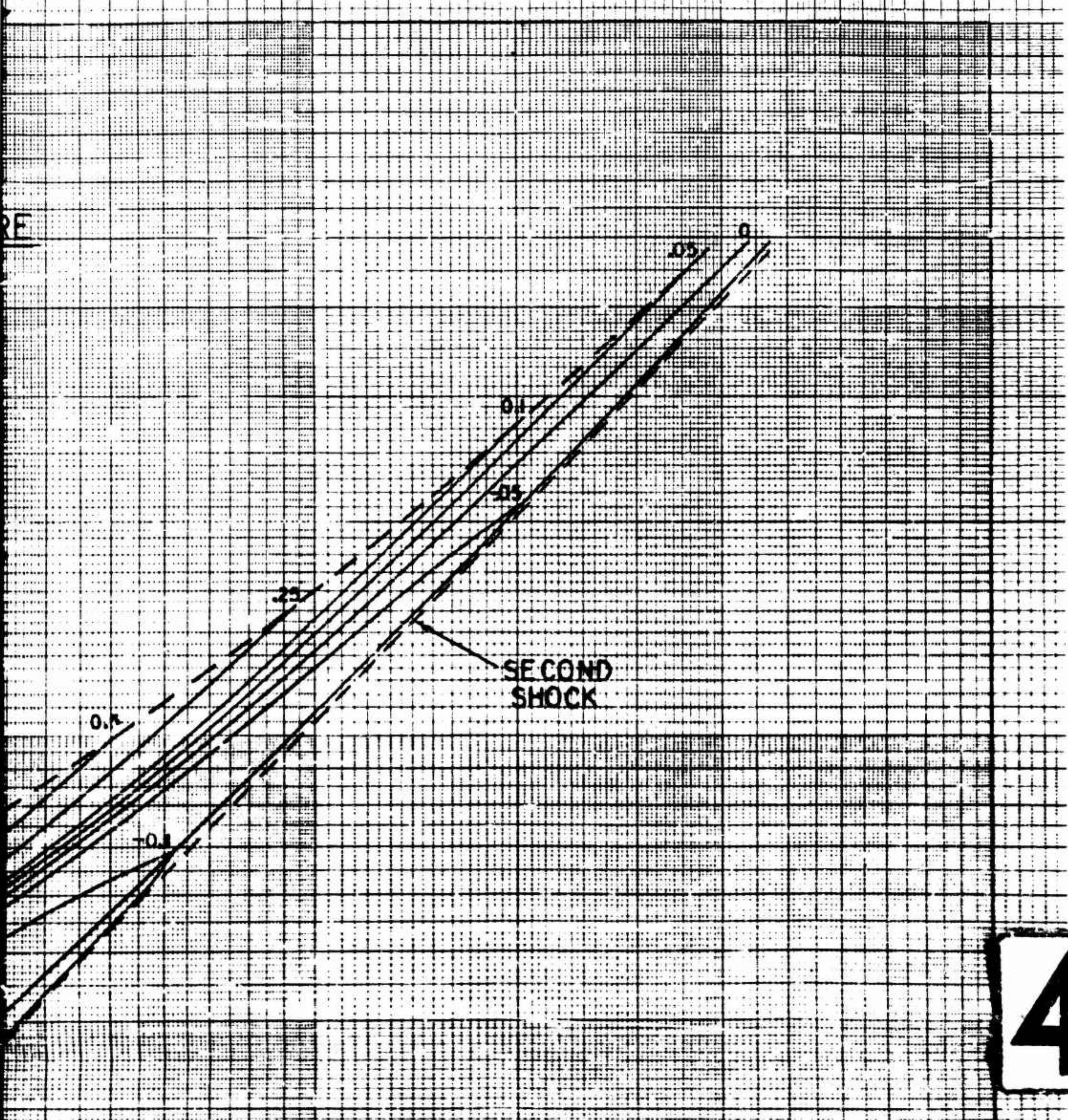
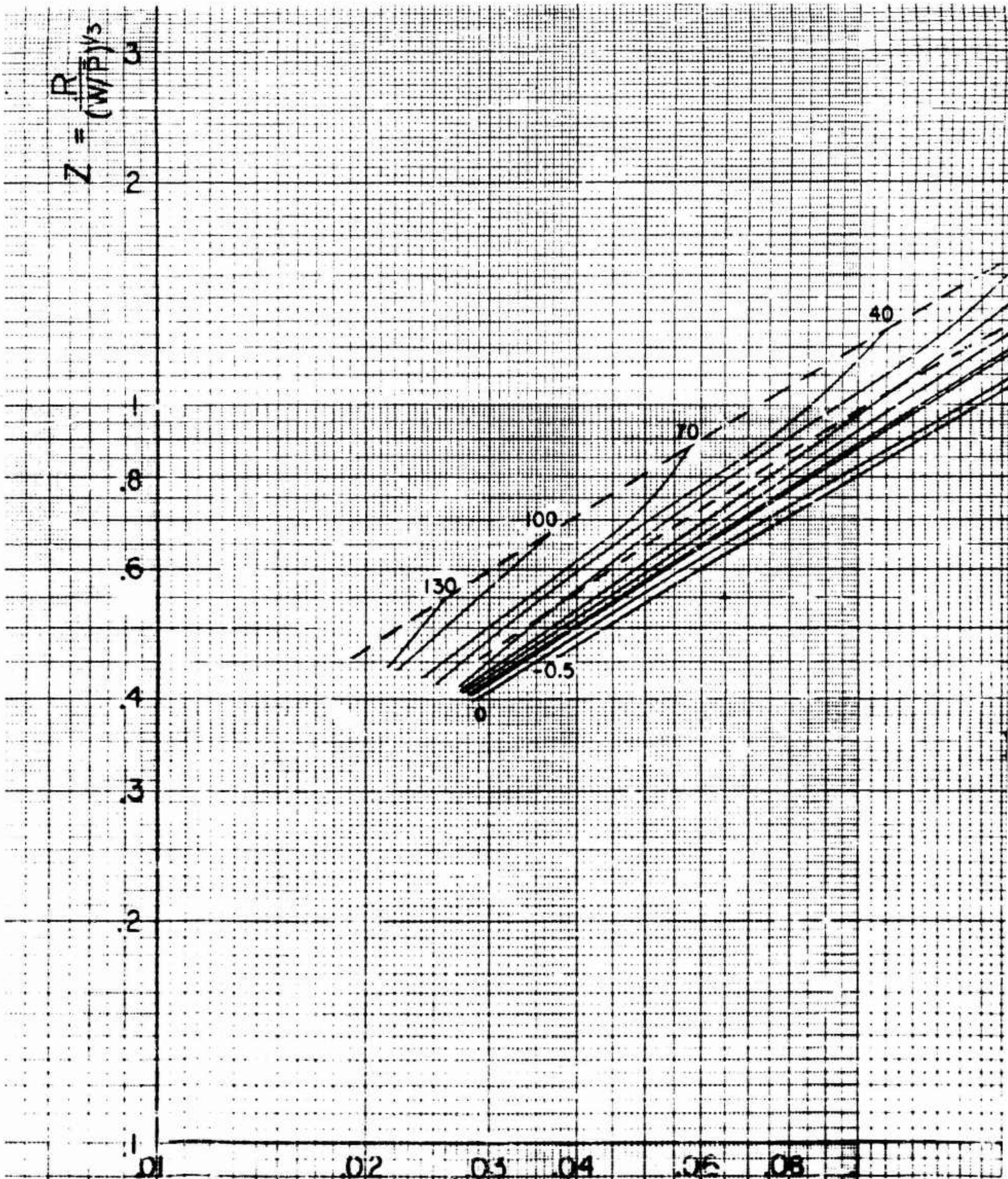


FIGURE 4



4



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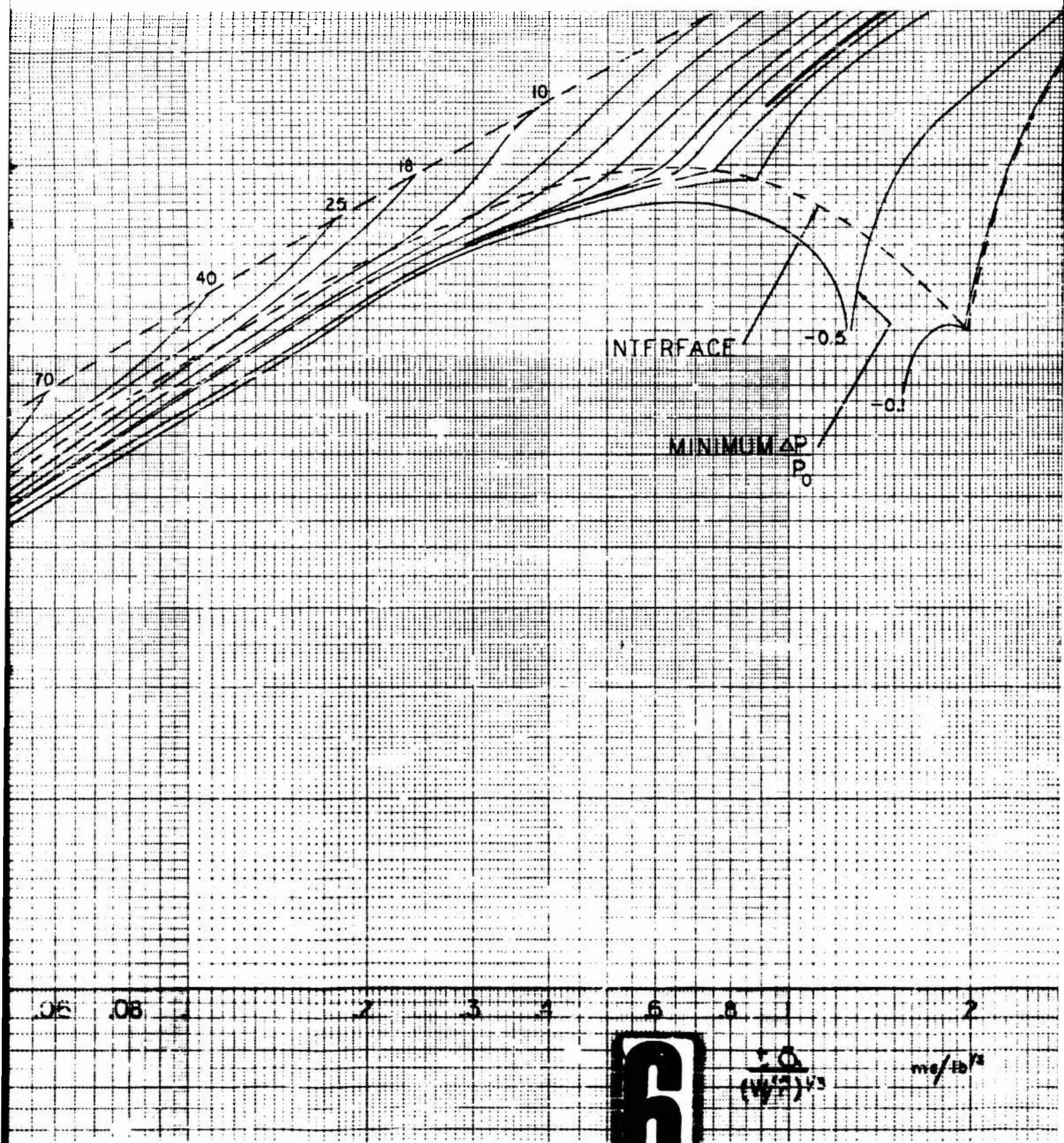
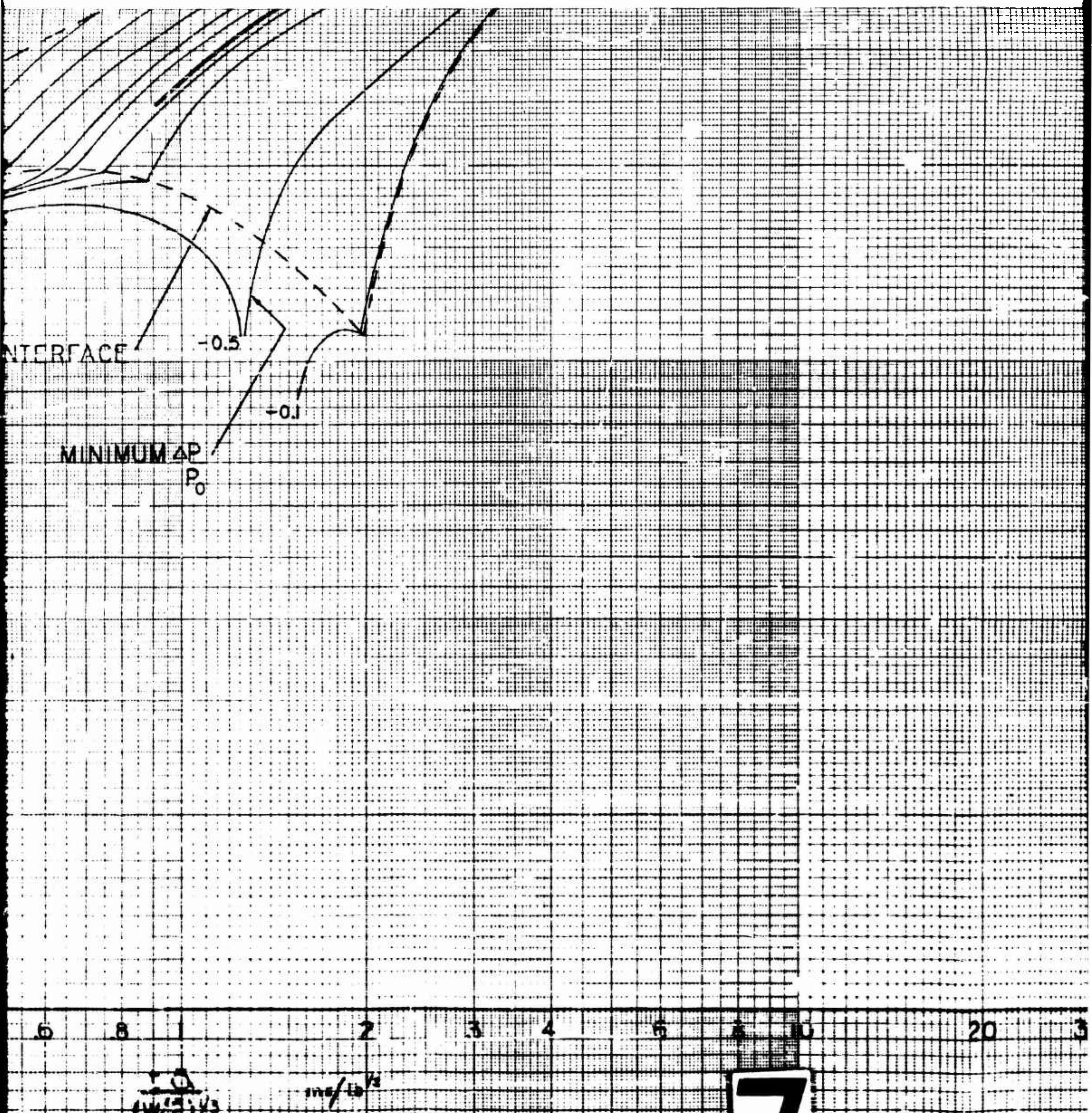
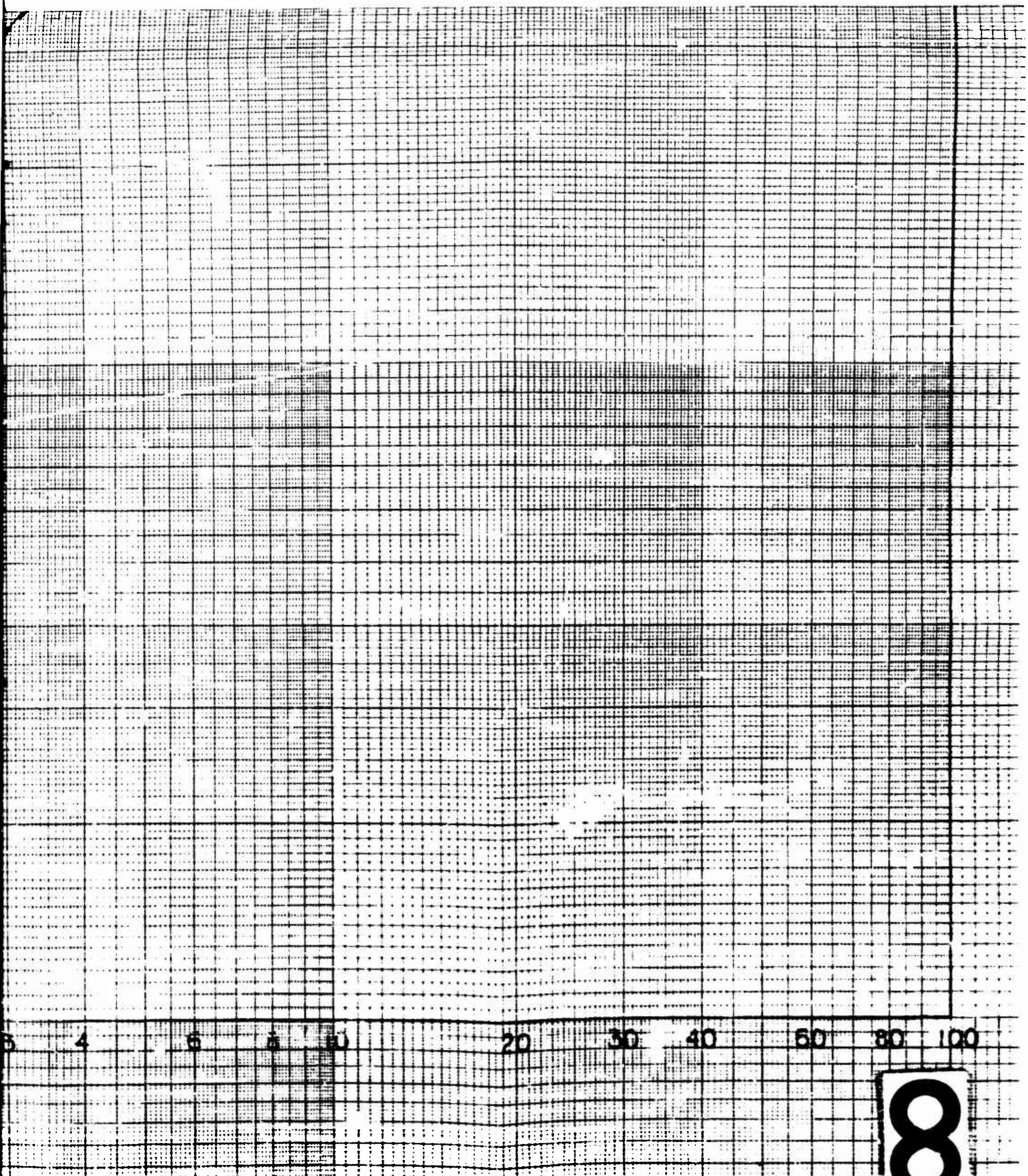


10
18
25
40
70
INTERFACE
-0.5
-0.1
MINIMUM $\frac{\Delta P}{P_0}$
.06
.08
.1
.2
.3
.4
.6
.8
1
2
6



NTERFACE
-0.5
-0.1
MINIMUM $\frac{\Delta P}{P_0}$
.6
.8
1
2
3
4
6
8
10
20
3
7



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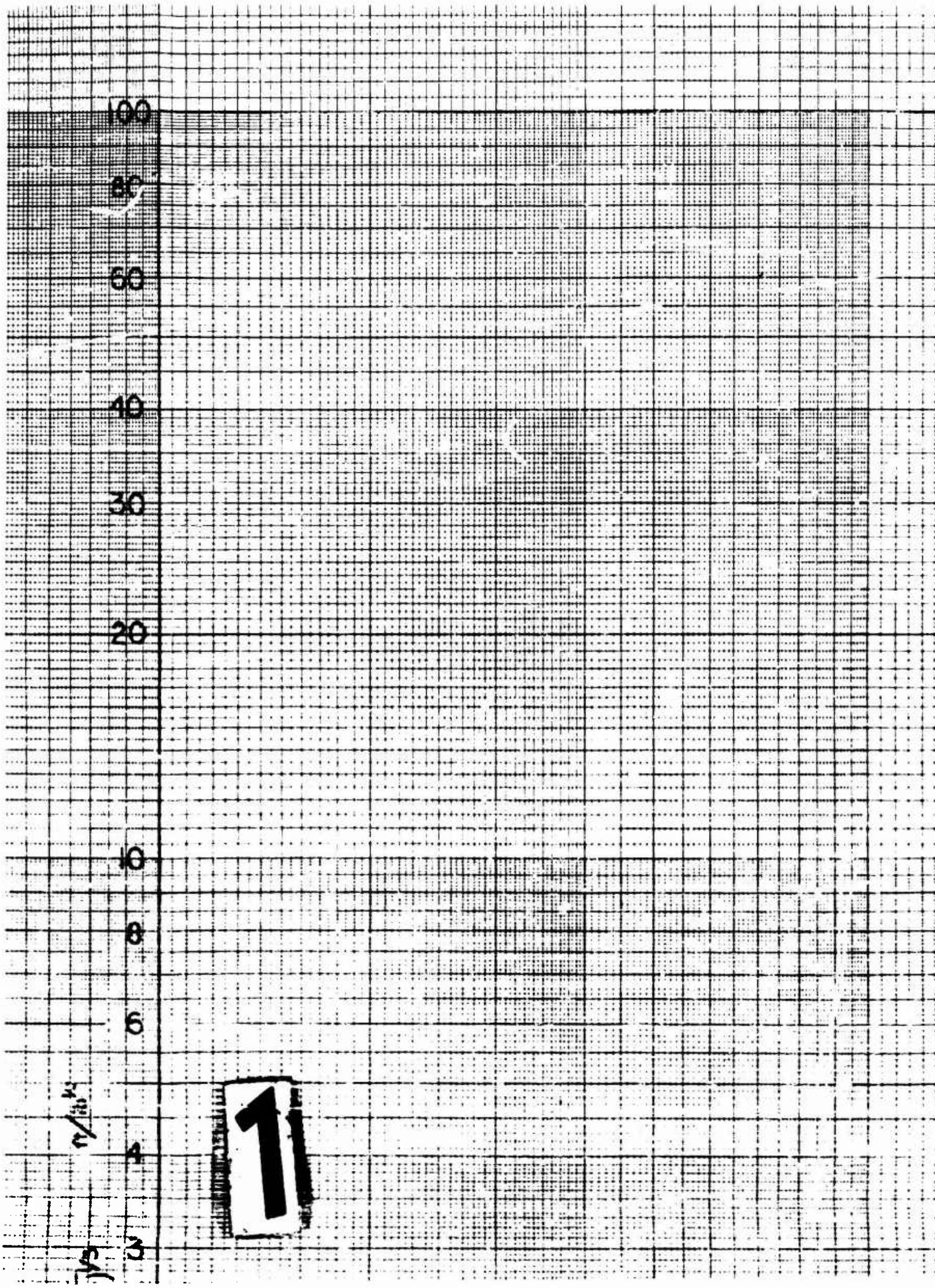
100
80
60
40
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20
10
8
6
4
3
1

FIGURE 5

TIME HISTORIES OF PARTICLE VELOICTY

$\frac{U}{a_0}$

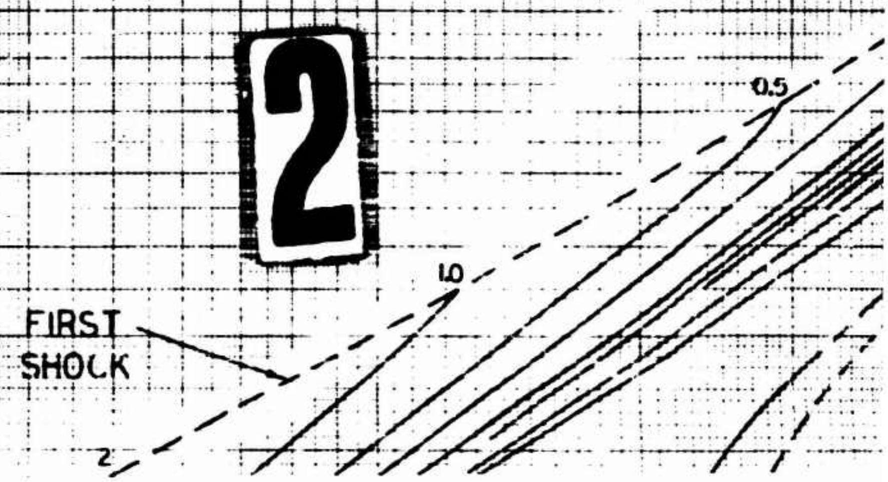
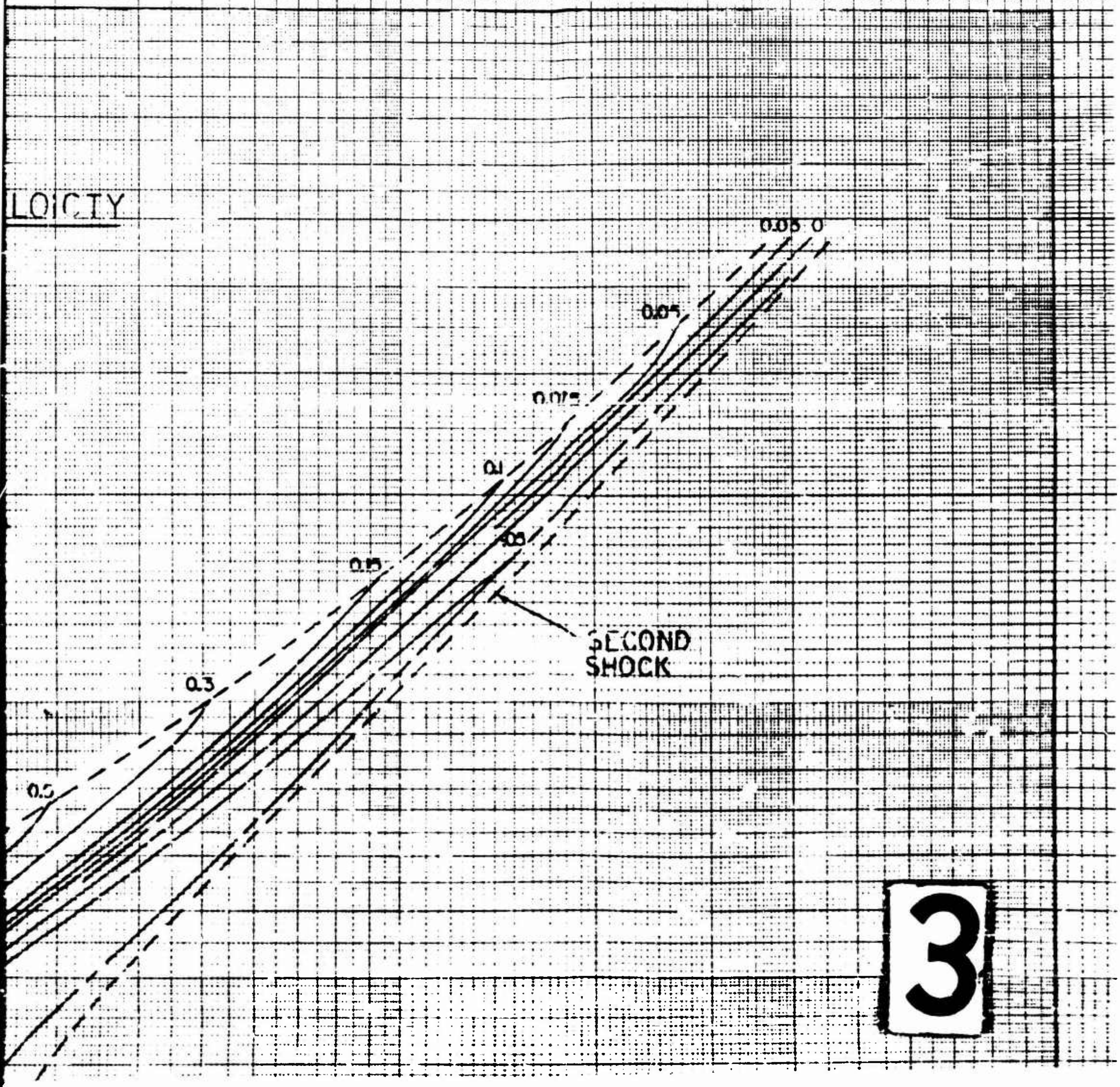
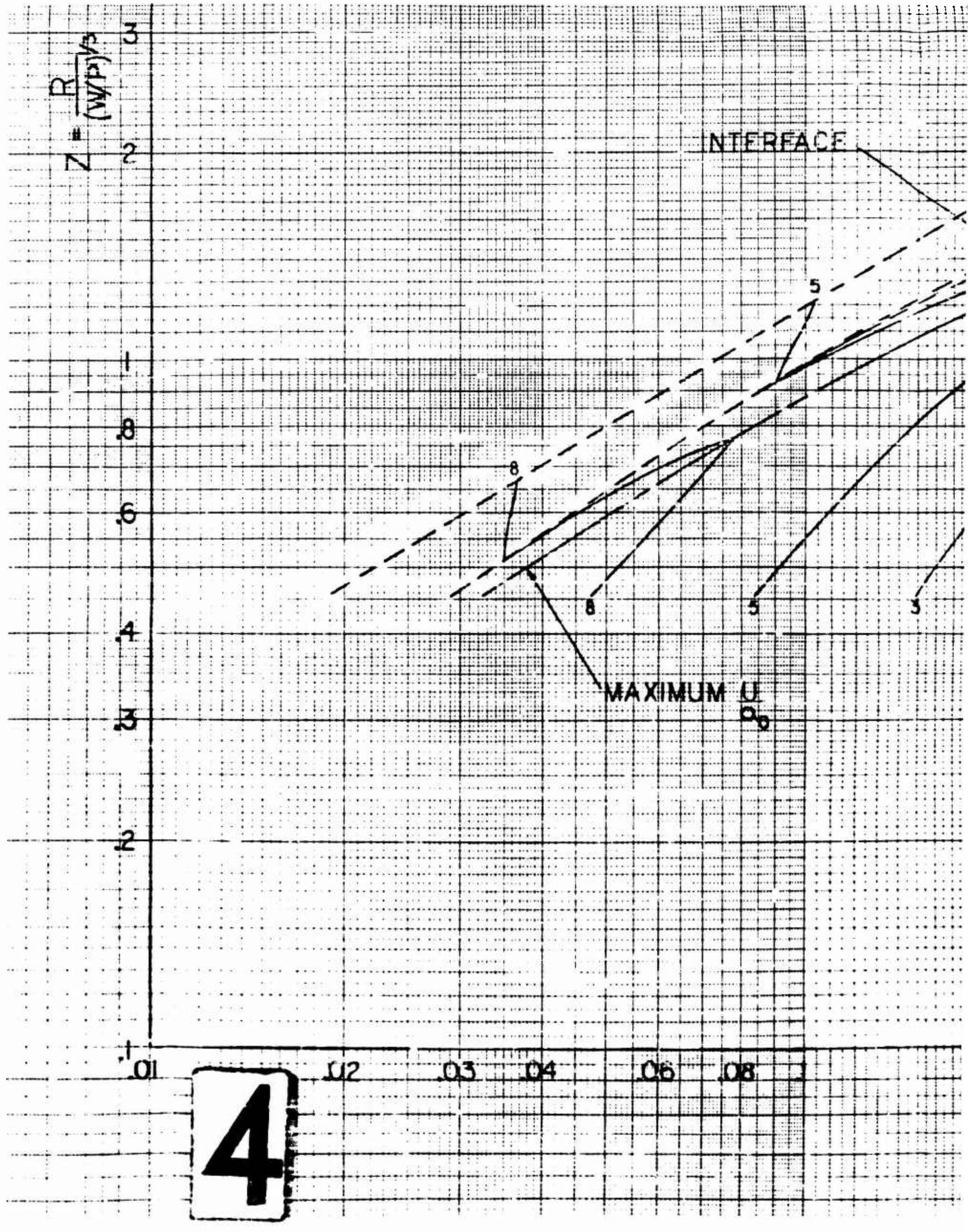


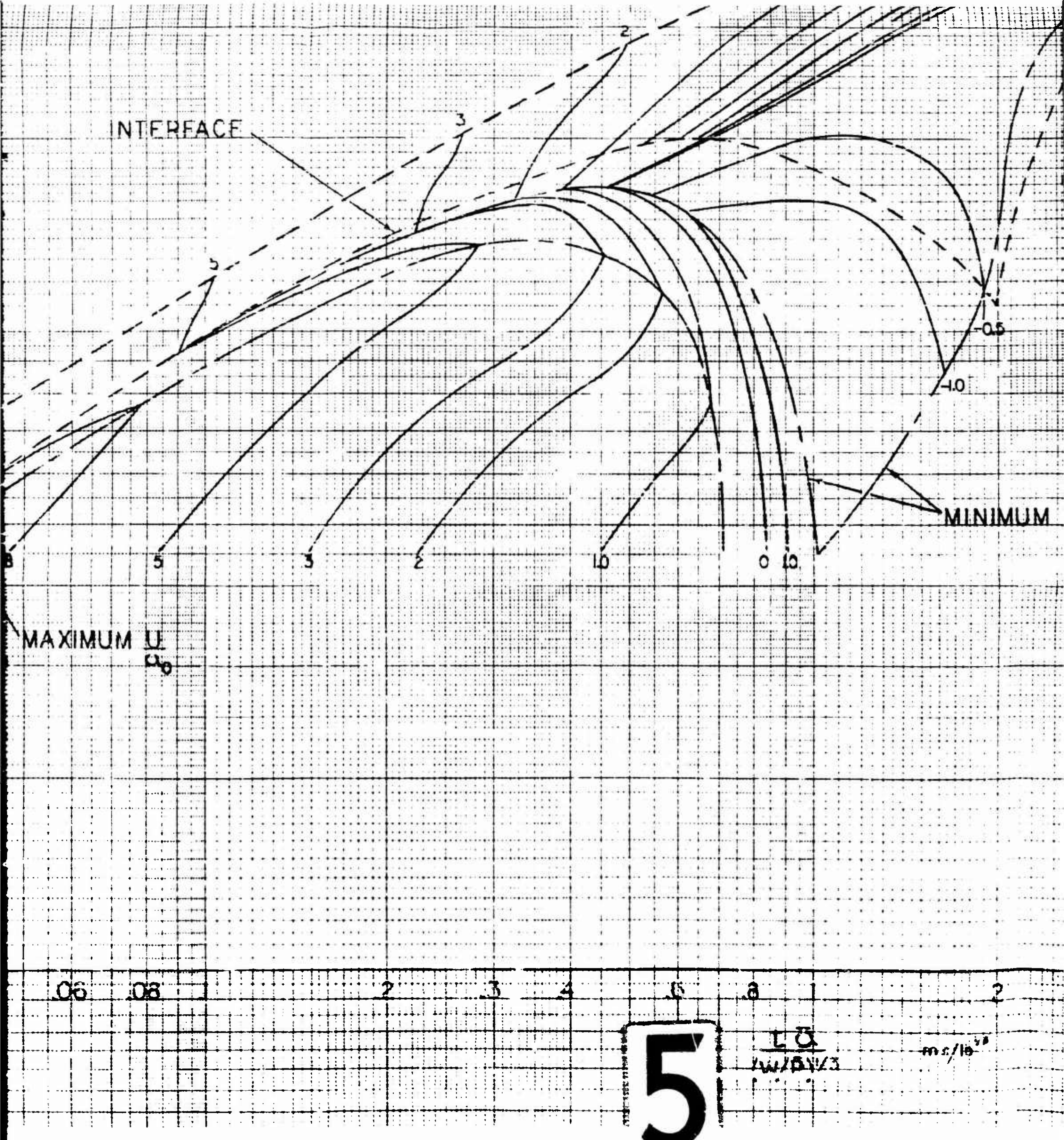
FIGURE 5





$Z = \frac{R}{(W/P)^{1/3}}$
3
2
1
.8
.6
.4
.3
.2
.1
INTERFACE
MAXIMUM $\frac{U}{a_0}$
8
5
3
.01
.02
.03
.04
.06
.08
.1

4



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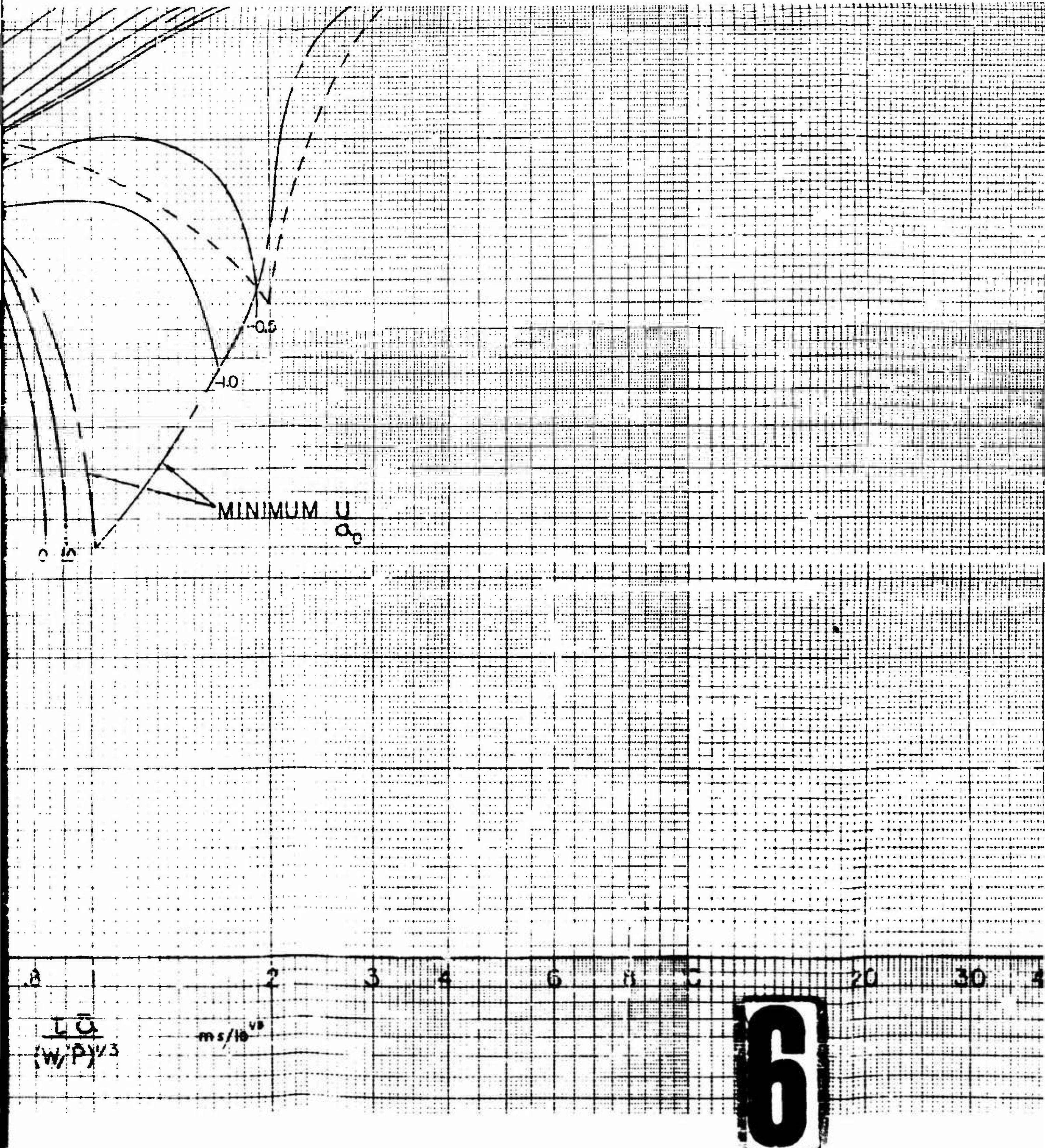
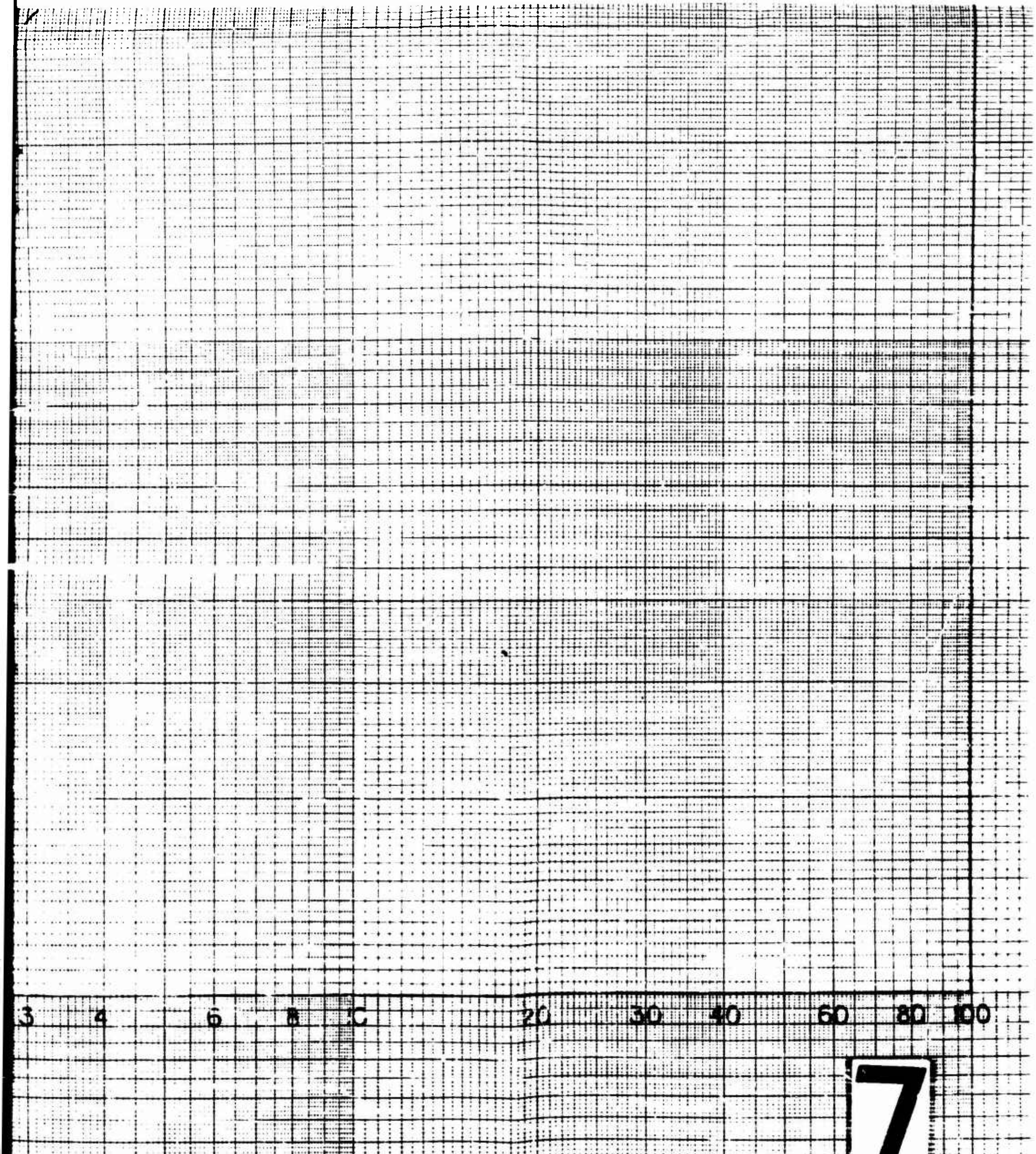

-0.5
-1.0
MINIMUM $\frac{U}{a_0}$
0
-1.0
.8
2
3
4
6
8
10
20
30
$\frac{t\,\bar{a}}{(W/P)^{1/3}}$
ms/lb$^{1/3}$
6



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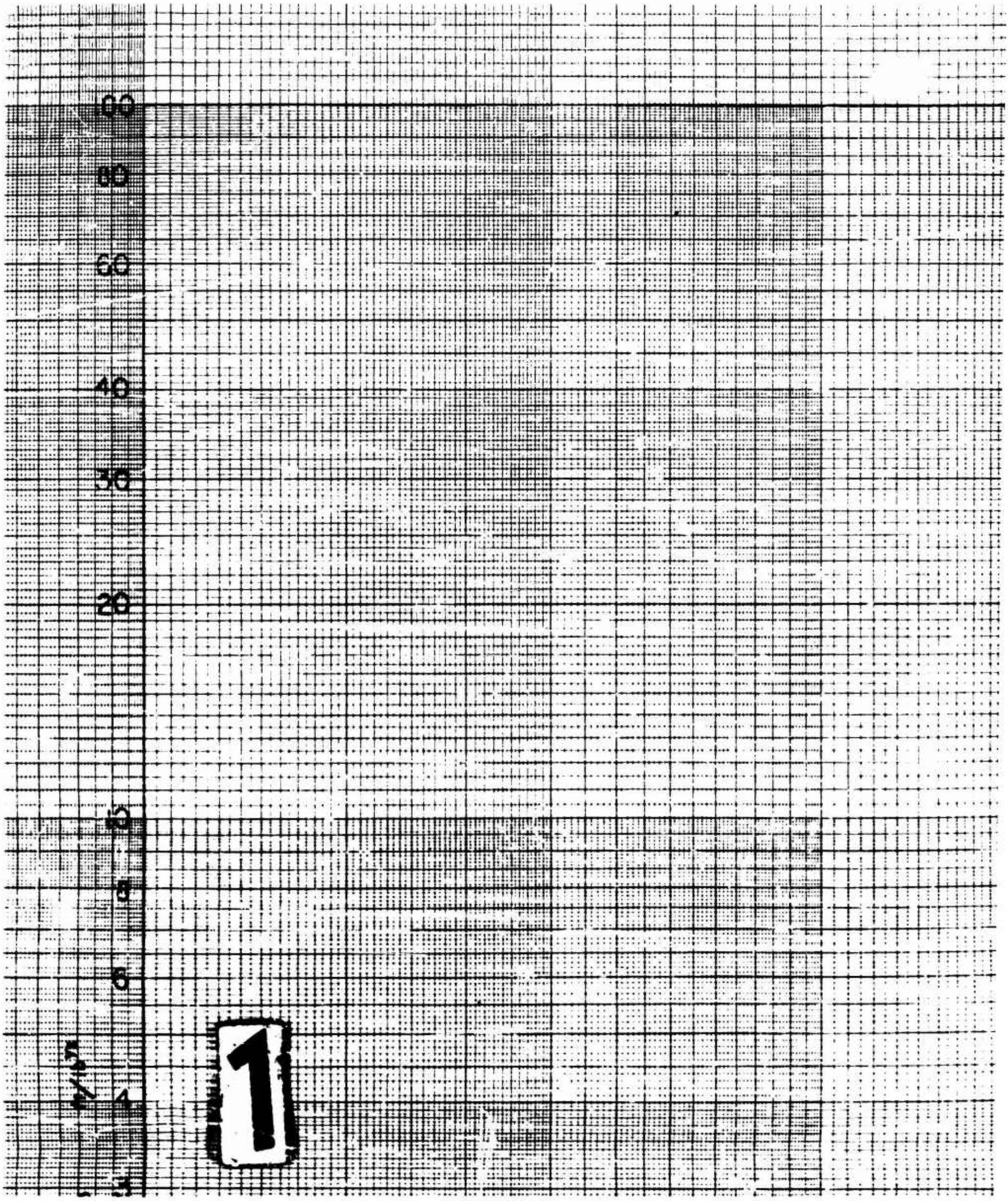
100
80
60
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20
10
8
6
4
3
1

FIGURE 6

TIME HISTORIES OF DENSITY

$\frac{\rho_3}{\rho_0}$

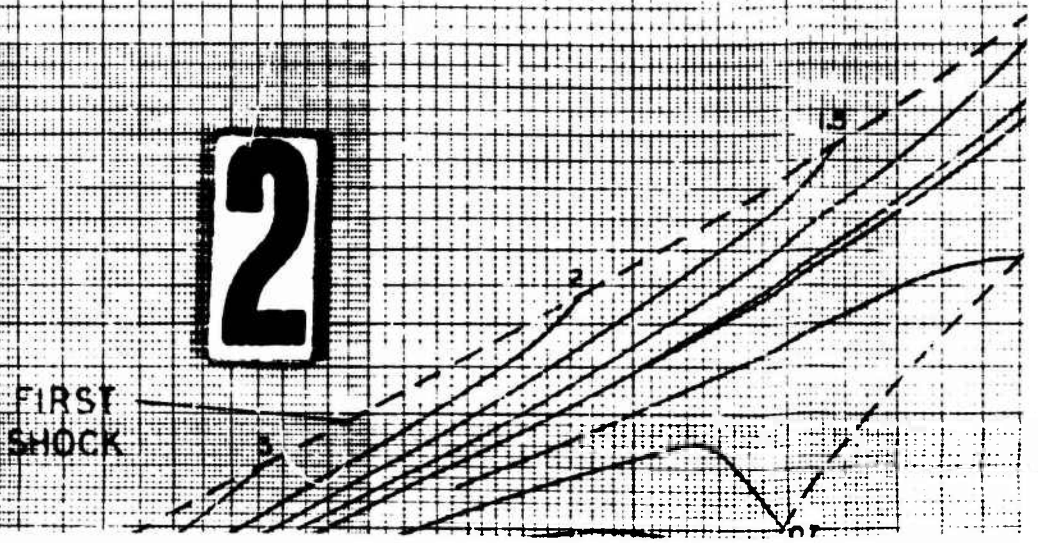
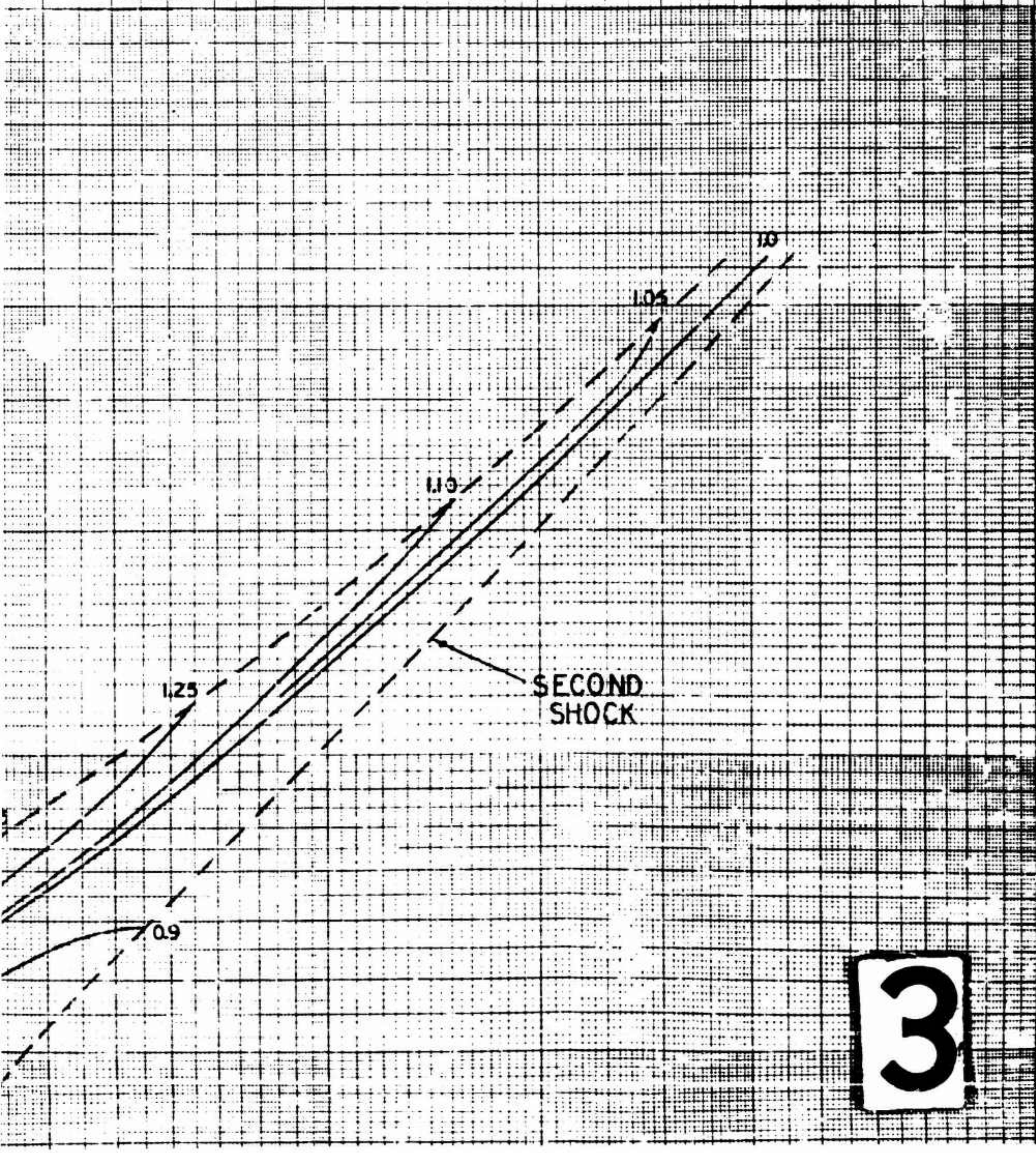
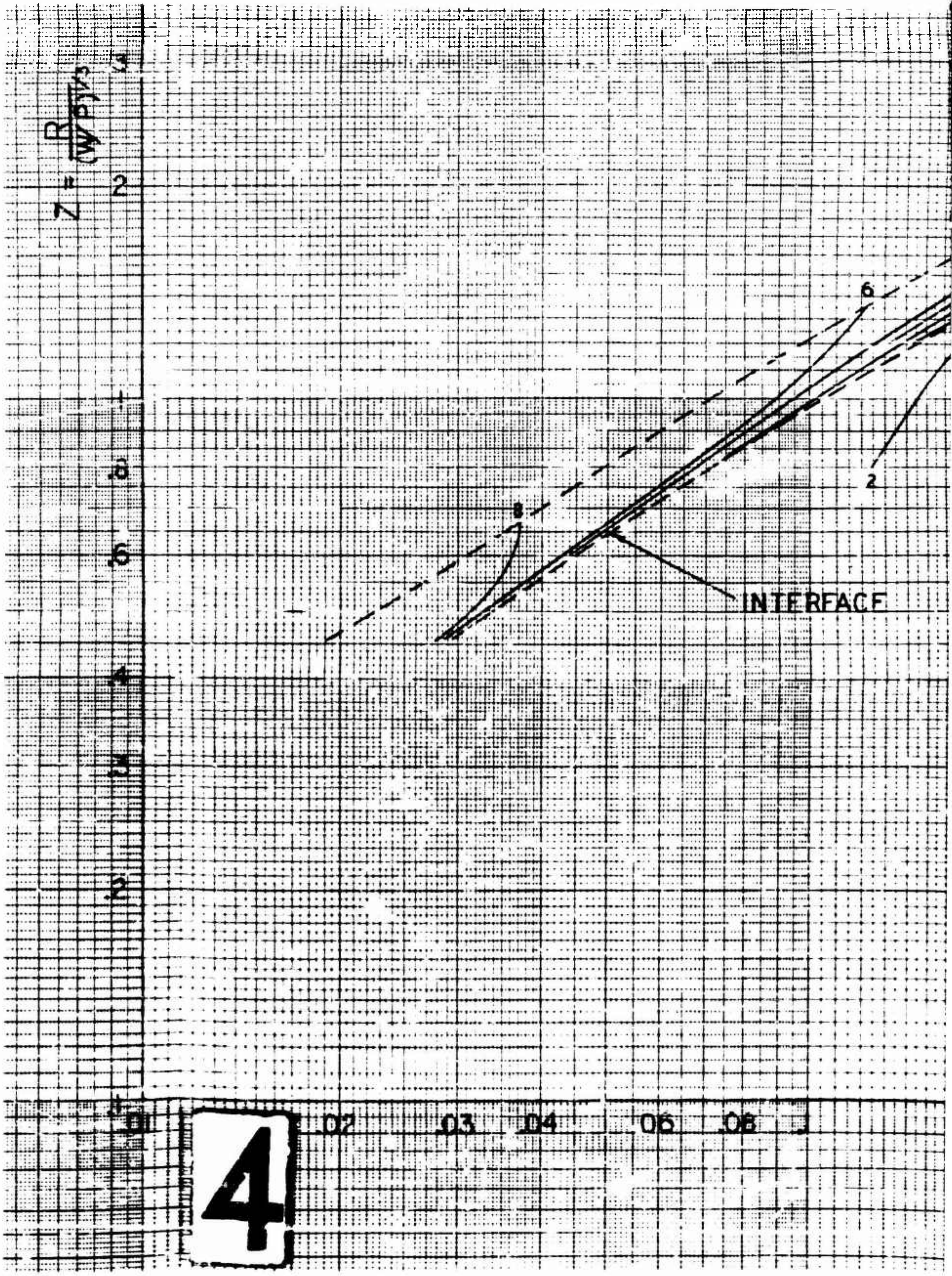


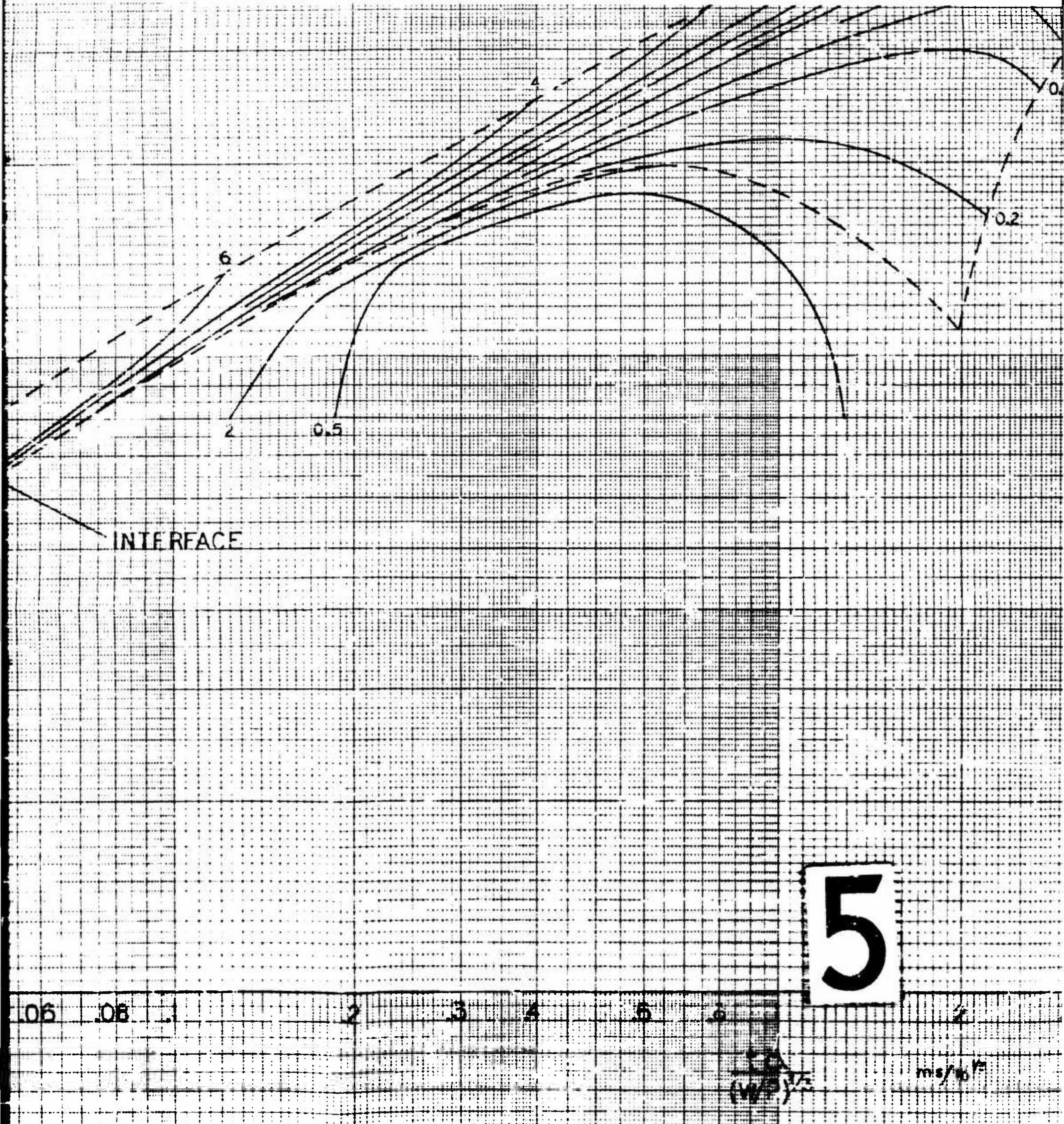
FIGURE 6



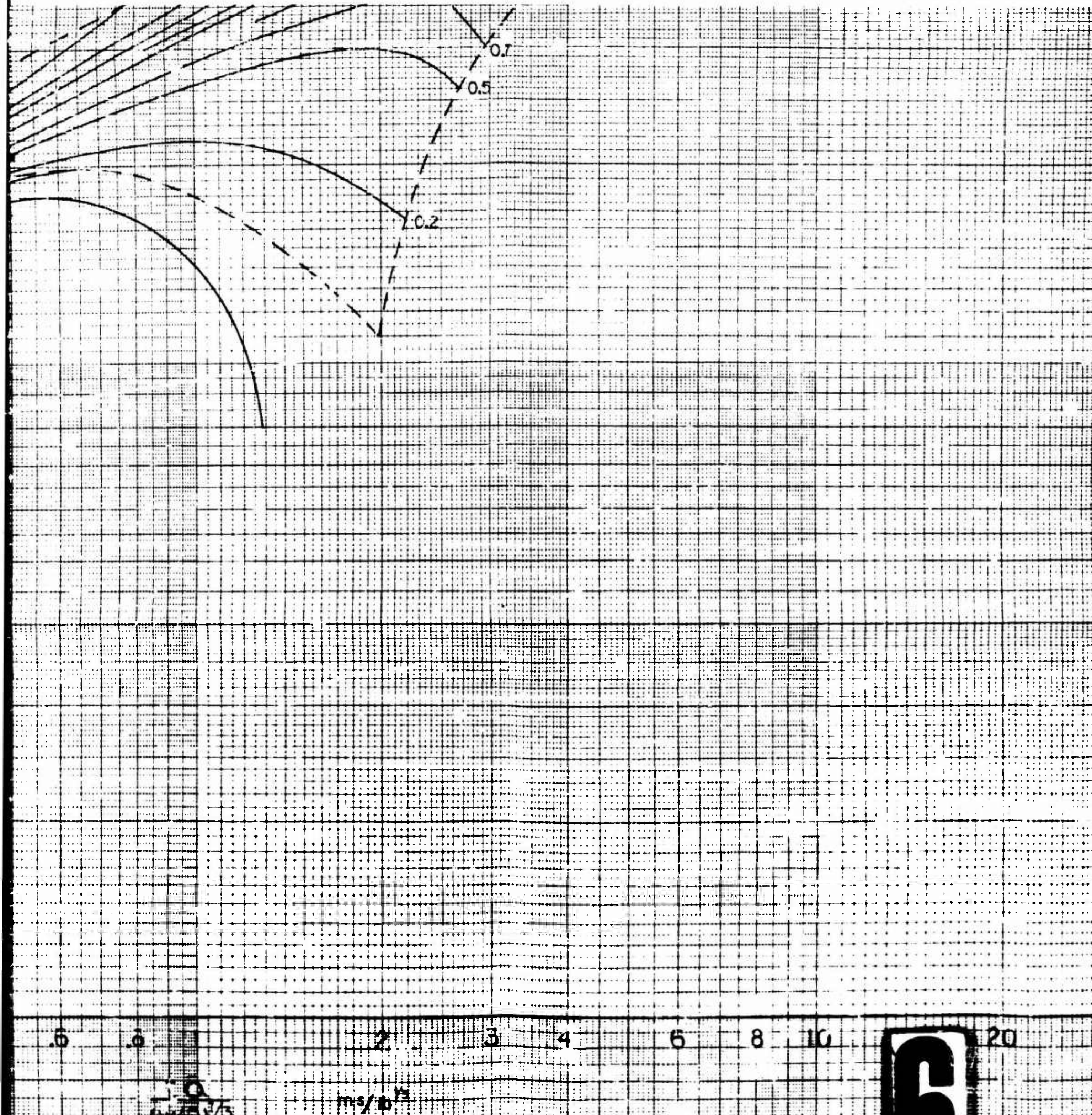
3



$Z = \frac{R}{(W/P)^{1/3}}$
4
2
1
.8
.6
.4
.3
.2
.01
.02
.03
.04
.06
.08
.1
6
2
8
INTERFACE
4



5



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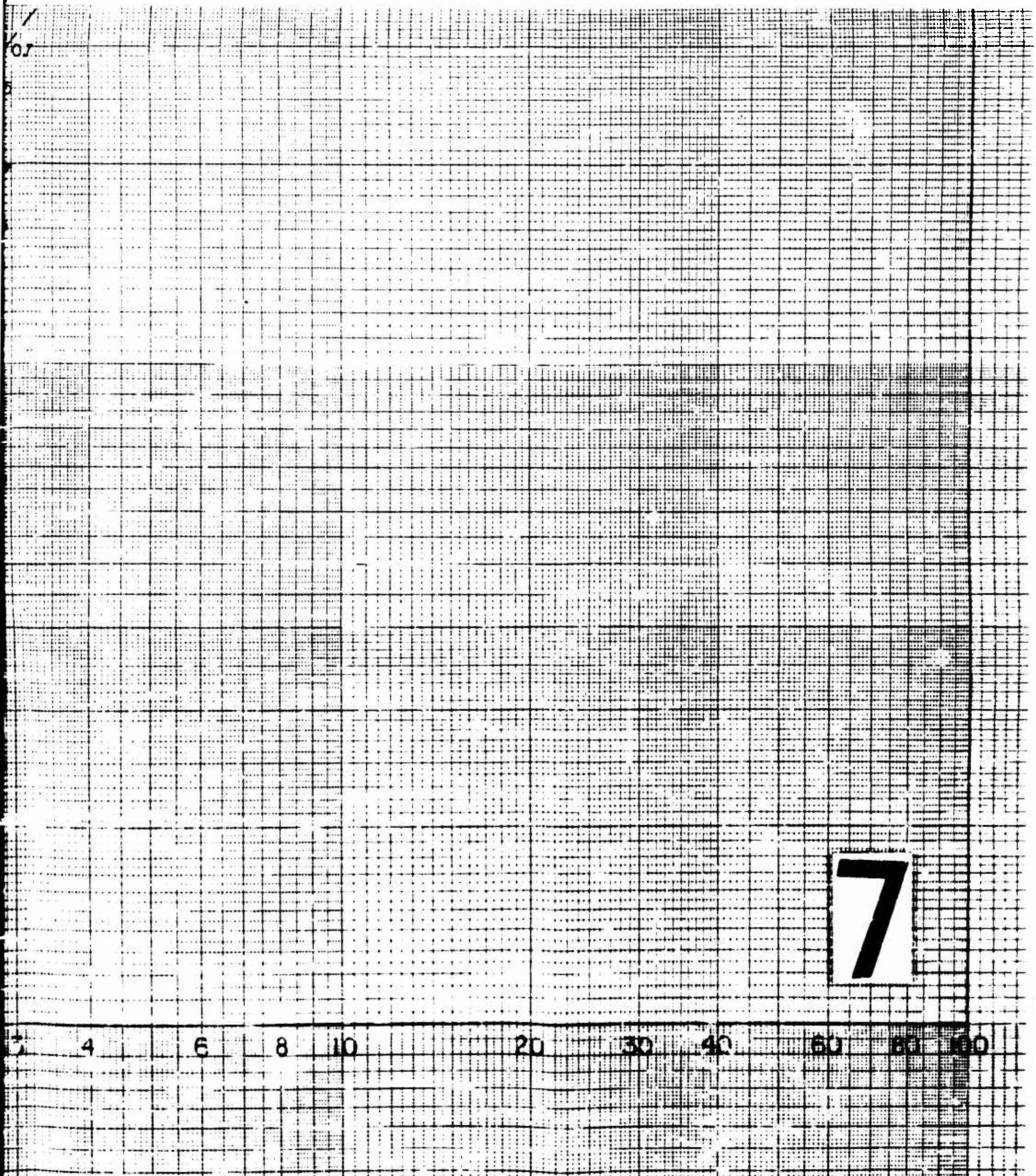
4
6
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7

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13. ABSTRACT

This report presents in a convenient, graphical format a self-consistent set of blast wave properties for a TNT explosive. Summaries of the contents of various sources of pertinent experimental data are given in this report, together with evaluations of these data in order to justify the use of only a selected number of these sources. Discussions of various theoretical methods of predicting blast wave characteristics are also given in this report. (U)

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